Biowaste home composting: Experimental process monitoring and quality control

Fabio Tatàno*, Giacomo Pagliaro, Paolo Di Giovanni, Enrico Floriani, Filippo Mangani

DiSBeF - Department of Basic Sciences and Foundations, Section of Bio-Mathematics, Environmental Modeling and Engineering, University of Urbino "Carlo Bo", Campus Scientifico "E. Mattei", 61029 Urbino, Italy

* Corresponding Author. Tel.: +39 0722 304 264; fax: +39 0722 304 275.

E-mail address: fabio.tatano@uniurb.it (F. Tatàno).

ABSTRACT

Because home composting is a prevention option in managing biowaste at local levels, the objective of the present study was to contribute to the knowledge of the process evolution and compost quality that can be expected and obtained, respectively, in this decentralized option. In this study, organized as the research portion of a provincial project on home composting in the territory of Pesaro-Urbino (Central Italy), four experimental composters were first initiated and temporally monitored. Second, two small sub-sets of selected provincial composters (directly operated by households involved in the project) underwent quality control on their compost products at two different temporal steps. The monitored experimental composters showed overall decreasing profiles versus composting time for moisture, organic carbon, and C/N, as well as overall increasing profiles for electrical conductivity and total nitrogen, which represented qualitative indications of progress in the process. Comparative evaluations of the monitored experimental composters also suggested some interactions in home composting, i.e., high C/N ratios limiting organic matter decomposition rates and final humification levels; high moisture contents restricting the internal temperature regime; nearly horizontal phosphorus and potassium evolutions contributing to limit the rates of increase in electrical conductivity; and prolonged biowaste additions contributing to limit the rate of decrease in moisture. The measures of parametric data variability in the two sub-sets of controlled provincial composters showed decreased variability in moisture, organic carbon, and C/N from the seventh to fifteenth month of home composting, as well as increased variability in electrical conductivity, total nitrogen, and humification rate, which appear to be conditions that are compatible with the respective nature of decreasing and increasing parameters during composting. The modeled parametric kinetics in the monitored experimental composters, along with the evaluation of the parametric central tendencies in the sub-sets of controlled provincial composters, all indicate that 12-15 months is a suitable duration time for the appropriate development of home composting in final and simultaneous compliance with typical reference limits.

Keywords:

Biowaste

Home composting

Kinetics

Process monitoring

Quality control

Time

1. Introduction

In accordance with the framework waste legislation (Directive 2008/98/EC), the European Union’s approach to solid waste management is based on an integrated, hierarchical system with waste prevention as the highest priority. In line with this priority, and to comply with the further requirement of the European landfill directive (1999/31/EC) to progressively reduce the amount of municipal biodegradable waste going to landfills, prevention measures and programs are expected and particularly encouraged for the biowaste category, followed by recovery options based on separate collection and biological treatment systems for biowaste that cannot be prevented (European Commission, 2010). Moreover, the European strategy for waste prevention generally calls for prevention actions to be taken at all geographical scales of governance, including regional and local levels (European Commission, 2005).

At local territorial levels, the combined option of segregating domestic biodegradable waste at the source and directly destining it to home composting may be seen as a valuable prevention action contributing to reduce the generation of household waste (Onida, 2000; Cox et al., 2010). In fact, biowaste home composting closes the material loop directly at the source place (usually, the owned garden or land) and does not imply any external waste collection, transport, or management actions (with their related costs) nor should any residual waste be generated by the locally performed process (Onida, 2000; Zurbrügg et al., 2004; Adhikari et al., 2010). However, while the alternative and predominant recovery option of centralized composting of organic waste has been widely studied and developed at the industrial level and well addressed in international waste/biowaste management handbooks (Tchobanoglous et al., 1993; Krogmann et al., 2010; Epstein, 2011), biowaste home composting has only recently begun to be analyzed from a technical and scientific perspective (Colón et al., 2010). In particular, some studies have recently been focused on the following issues with biowaste home composting: (1) citizen attitude and behavior as evaluated by investigations including interviews, questionnaires, and focus groups (Tucker et al., 2003; Curtis et al., 2009); (2) the quantitative impact in terms of amounts of avoided waste per household and unit time (Smith and Jasim, 2009; Cox et al., 2010; Sharp et al., 2010); and (3) the environmental assessment of the entire process based on the life cycle assessment methodology, with the preliminary individuation of the pertaining inventories (McKinley and Williams, 2007; Amlinger et al., 2008; Andersen et al., 2011, 2012; Colón et al., 2010).

In conjunction with the quantitative and life cycle-based evaluations, a comprehensive technical-scientific view of biowaste home composting should also include increasing the currently limited knowledge of the process performance and efficiency in the composting units (Karnchanawong and Suriyanon, 2011; Ermolaev et al., 2014). Indicatively, a comparative study on the characterization of product samples from home and industrial composting, with particular attention to their stability, appeared only recently (Barrena et al., 2014). Therefore, it seems useful to make available complementary research studies focused on (1) the monitoring and analysis of the temporal evolution of the home composting process, and (2) the evaluation of the quality of compost products that can be obtained in practice by households implementing this decentralized approach. Both of these aspects were considered in the present experimental study, which was performed as the technical-scientific portion of a project on the local feasibility of home composting managed by the provincial authority in the territory of Pesaro-Urbino (Marche Region, Central Italy, Adriatic Sea side), where the University of Urbino is located. In particular, the provincial project involved the distribution of identical composters to over 1,600 households for the home composting of domestic biowaste for an extended period of fifteen months. In the technical-scientific research component of the project, firstly the temporal evolution of the home composting process was studied at the University of Urbino by initially organizing and temporally monitoring four experimental composters: two located in the coastal area of the two main provincial sea-towns and the other two in the inland area of the main provincial hilly-town. Then, to obtain an indication of the actual performance of home composting carried out by households directly involved in the provincial project, two small sub-sets of household composters were selected by the provincial authority according to a partly statistical procedure, and the respective product samples underwent quality control at the University of Urbino with the following temporal differentiation: (1) one intermediate characterization campaign on the first sub-set of composters, and (2) a final characterization campaign on the second sub-set of composters. For a realistic evaluation of the monitoring and control of biowaste home composting, the obtained characterization results (temporal profiles and related kinetic elaborations, univocal determinations, or data sub-sets) were compared with reference limits for several of the characterized parameters based on the Italian legislation (with an additional integration from a European specification).

2. Materials and methods

2.1. Process monitoring of experimental composters

The following experimental composters ("comp") located in the provincial territory of Pesaro-Urbino were initiated and temporally monitored (Fig. 1, left): (1) "comp-uni-u" composter, which served the scientific campus (canteen and green area maintenance) of the University of Urbino ("uni") situated in a green hilly area close to the historic town of Urbino ("u"); (2) "comp-house-u" composter, which served a detached house with a garden ("house") situated in the hilly municipal territory of Urbino; (3) "comp-residential-p" composter, which served a multi-occupancy residential building with a garden ("residential") situated in the municipal territory of the sea-town of Pesaro ("p"); and (4) "comp-rural-f" composter, which served a rural house with land ("rural") situated in the municipal territory of the sea-town of Fano ("f"). Each experimental composter was of the same type (model 310, Mattiussi Ecologia, Italy) as that adopted in the aforementioned provincial project, with the following characteristics (Fig. 1, right): polypropylene composition, truncate conical body, 92 cm in height and 80 cm in maximum diameter, volumetric capacity of 0.31 m^3, and equipped with a circular opening lid on the upper part (for biowaste addition) and a side sliding door on guides (for control, sampling, and final compost withdrawal). The cylindrical-shaped bottom had channels, slits, and an internal vertical cone with non-clogging holes to favor a natural aeration into the composter.

The experimental composters were placed outdoors in partial shading conditions, directly onto stable but uncompacted soil. The biowaste feeding operations began in spring (end of April) for all experimental composters and continued for a period of seven months in “comp-uni-u”, “comp-residential-p”, and “comp-rural-f” composters and for a total of thirteen months in “comp-house-u” composter. The experimental composters were fed approximately twice a week, which is a feeding frequency previously adopted in another study of home composting (Andersen et al., 2010). Each feeding operation generally consisted of a combination of the two complementary streams of biowaste (i.e., kitchen and green waste) mixed in a volumetric proportion of approximately 1:1. Referring indicatively to “comp-uni-u” and “comp-residential-p” composters, the resulting average weekly amounts of feeding mixture were 5.5 and 5.3 kg week^{-1}, respectively. Compared with relevant experimental studies on the life cycle assessment of home composting, these resulting average weekly amounts are within the range of weekly additions of biowaste mixture, with lower values of 2.7-3.7 kg week^{-1} reported by Andersen et al. (2010, 2011), and higher values of 11.4 and 18.0 kg week^{-1} reported by Martínez-Blanco et al. (2010) and Colón et al. (2010), respectively. Further, the resulting values of 5.3 and 5.5 kg week^{-1} are consistent with the overall range of average weekly additions of 4.6-6.9 kg week^{-1} reported by McKinley and Williams (2007) based on a literature review of home composting data.

The temporal monitoring of the home composting process relied on the determination of the following parameters for each experimental composter: (1) moisture, pH, electrical conductivity, and volatile solids, determined on a monthly basis from the second to the tenth month since the biowaste feedings began; (2) total nitrogen, extractable phosphorus (as P_2O_5) and potassium (as K_2O), determined on a monthly basis from the sixth-seventh to the tenth month since the biowaste feedings began; and (3) a conclusive characterization of all previous parameters in the thirteenth month since the biowaste feedings began along with the additional determination of humified organic carbon (HA + FA, the combined humic and fulvic acid fractions) and heavy metals (cadmium, chromium, copper, lead, nickel, and zinc). The mixture samples for these determinations were collected through the composter lateral access (Fig. 1, right). The internal temperature was recorded in two experimental composters ("comp-uni-u" and "comp-residential-p"). Specifically, the temperature monitoring was performed twice weekly for "comp-uni-u" composter from the second to the eighth month of home composting and on a daily basis for "comp-residential-p" composter from the second to the sixth month (first ten days) of home composting.

2.2. Selection and compost quality evaluation of the sub-sets of provincial composters

To select the aforementioned small sub-sets of provincial households directly involved in the home composting project at the provincial territorial level of Pesaro-Urbino, a descriptive statistical analysis (in terms of resulting frequency distributions) was initially performed on the categorical household characteristic data from the completed questionnaires that were originally distributed by the provincial authority to the households experimenting with home composting. Then, a cascading data filtering procedure was organized in a computer worksheet by purposely extracting at each filter step households belonging to the predominant category within each of the following characteristics (in cascading order): (1) the number of persons per household; (2) the household education level; (3) the extension of available garden/land; and (4) the housing location. As a result of this applied procedure, a statistically filtered and limited group of representative households was obtained from the overall set of households that completed questionnaires. Finally, within this representative group, the provincial authority autonomously selected two different small sub-sets of households, consisting of fourteen and thirteen units. The compost samples were directly collected by the provincial authority from the selected sub-sets of household composters in two different temporal steps; then, the anonymous samples were delivered to the University of Urbino, and the following quality control campaigns were performed: (1) for the first sub-set of fourteen household compost samples, collected in an intermediate step (i.e., the seventh month since the beginning of the provincial home composting project), moisture, pH, electrical conductivity, volatile solids, humified organic carbon, total nitrogen, extractable phosphorus and potassium, heavy metals (cadmium, chromium, copper, lead, nickel, and zinc), and *Salmonella* were determined; and (2) for the other sub-set of thirteen household compost samples, collected at the end of the provincial home composting project (i.e., fifteen months after the project began), the previous parameters were determined, with the exception of heavy metals and *Salmonella*.

2.3. Analytical procedures and considered reference limits

The analytical procedures for the aforementioned parametric determinations were performed in general accordance with the analytical methods published by the Italian Environmental Protection Agency (ANPA, 2001) and the Italian Ministry of Agriculture and Forestry (Italian Ministry of Agriculture and Forestry, 2000). In particular, the volatile solids determination was assumed to be indicative of the organic matter content (ANPA, 2001). Consequently, the total organic carbon (TOC) content was calculated by multiplying the organic matter content by 0.58 (according to the "Van Bemmelen" conversion factor: Italian Ministry of Agriculture and Forestry, 2000; European Commission, 2006). Based on the available HA + FA and TOC contents, a pertinent humification parameter was derived, namely the humification rate (HR) defined as the percentage of HA + FA with respect to TOC (Tomati et al., 1995; ANPA, 2001). Internal temperature monitoring in "comp-uni-u" and "comp-residential-p" composters was performed using a portable thermocouple. Ambient temperatures were obtained from the recorded daily data from the Meteorological Observatory "Serperi" of the University of Urbino relating to the weather station located on the scientific campus, for comparison with "comp-uni-u" composter, and from the Seismic-Meteorological Observatory "Valerio" relating to the weather station located in Pesaro, for comparison with "comp-residential-p" composter.

The compost reference limits assumed in this study are reported in Table 1. These limit values were primarily derived from the Italian Legislative Decree No. 75/2010 on fertilizers (as amended by the subsequent Ministerial Decree No. 10.07.2013) with reference to the soil improver category of biocompost (or alternately definable as composted mixed soil improver), which is generable from source-separated organic waste inclusive of the organic fraction of municipal solid waste (MSW) and green and vegetable waste. Specifically, the limit value for chromium was obtained from the European eco-label criteria for soil improvers (European Commission, 2006), and those for total nitrogen, phosphorus, and potassium were from the original Italian Resolution No. 27.07.1984 on MSW compost.

2.4. Statistical analysis of monitoring and quality control data

For the monitored experimental composters, simple statistical measures were first calculated for the internal and ambient temperature data sets characterizing "comp-uni-u" and "comp-residential-p" composters. Then, given a general assumption of first-order kinetics for the expected temporal decay of organic matter or contaminants in a solid matrix during a composting process (In et al., 2007; Kuhad et al., 2011), monthly parametric measures that visually showed an overall temporal decrease were modeled with a first-order curve of the typical form:

$$P_{m,t} = P_{m,0} \cdot e^{(-k \cdot t)} \qquad (1)$$

where $P_{m,0}$ is the starting parametrical value, t is the composting time in months, and k is the rate constant in units of reciprocal time. Differently, monthly parametric measures that visually showed an overall temporal increase, or at least such a presumable trend, were evaluated with a zero-order relationship (Kuo, 1999), representable with a typical straight line form:

$$P_{m,t} = P_{m,0} + k \cdot t \qquad (2)$$

where $P_{m,0}$ is the vertical intercept, and the line slope k represents the rate constant expressed in the given parametrical units associated with reciprocal time.

For the selected provincial composters, the parametric data sub-sets obtained from each quality control campaign were statistically evaluated through the visual summary provided by the box-and-whisker plot approach (Anderson and Finn, 1996). Typically, this plot consists of a box running from the lower to the upper quartiles, with a horizontal segment at the location of the middle quartile. Thus, the box itself compactly conveys both a robust measure of central tendency, the median, and a robust measure of variability, the interquartile range (IQR, i.e., the difference between the upper and lower quartiles) (Giudici, 2003). This graphical representation is completed with two vertical segments (whiskers) extending from the box to the smallest and largest measures within 1.5 times the IQR, and any possible outliers are marked individually outside the whiskers. To confirm the visual indications of data asymmetry also derivable from the box-and-whisker plots, the provincial data sub-sets for some parameters were further evaluated by computing the asymmetry (or skewness) index, defined as the third central moment divided by the standard deviation cubed (Giudici, 2003).

The regression analysis of the exponential or linear fitting procedure, the box-and-whisker plot generation, and the asymmetry index determination were conducted using KaleidaGraph (version 4.0, Synergy Software).

3. Results and discussion

3.1. Monitored experimental composters

3.1.1. Temperature profiles

Fig. 2 shows the temperature profiles monitored in two experimental composters. For “comp-uni-u” composter, the left side of Fig. 2 shows an internal temperature profile characterized by an initial increase followed by a decrease finally approaching ambient temperature, which can be traced back to the typical rise and fall change in temperature with time expected in the traditional windrow composting (Tchobanoglous et al., 1993). Conversely, “comp-residential-p” composter presented in the right side of Fig. 2 a fluctuating temperature profile. The composters in available experimental studies (on gas emission from and environmental assessment of home composting and comparing differently configured units) effectively reflected the possible diversity of resulting temperature profiles: assimilable to a rise and fall behavior (Karnchanawong and Suriyanon, 2011; Adhikari et al., 2013), presenting significant fluctuations (Amlinger et al., 2008; Colón et al., 2012), closely following seasonal changes (Andersen et al., 2010). In terms of microbial temperature regimes (Diaz et al., 2002), the ranges of internal temperatures reported in Table 2 indicate that "comp-uni-u" composter developed both mesophilic and thermophilic conditions up to a recorded maximum value of 58°C, whereas only mesophilic conditions characterized "comp-residential-p" composter up to a recorded maximum value of 38°C. Because diversified microbial populations generally evolve and dominate during a small-scale composting process (Ryckeboer et al., 2003), chances are that, in any given instant in time in mesophilic or thermophilic conditions, internal temperature results effectively appropriate for some microbial group (Diaz et al., 2002). In particular, the overall development of exothermic microbial activity (Diaz and Savage, 2007; Smith and Jasim, 2009; Stentiford and de Bertoldi, 2010) in both experimental composters, although under the aforementioned differences in the microbial operating conditions, is revealed in Table 2 by the increase in internal temperature of 5.4 and 16.9°C (average) or 5.2 and 12.8°C (median) above ambient temperature in "comp-residential-p" and "comp-uni-u" composters, respectively.

3.1.2. Temporal evolutions of moisture, pH, and electrical conductivity

Fig. 3 shows the resulting temporal evolutions of moisture (upper diagram), pH (central diagram), and electrical conductivity (lower diagram) in the monitored experimental composters. Except for the initial monitoring months (from the second to the fourth/fifth) in two composters (i.e., "comp-rural-f" and "comp-residential-p"), the upper diagram of Fig. 3 shows overall decreases in measured moisture contents versus monthly composting time, which can be seen as indicative of progress in the composting process (de Bertoldi et al., 1990; Liu et al., 2011). However, only two experimental composters (i.e., "comp-rural-f" and "comp-residential-p") had moisture contents less than the corresponding upper limit from Table 1 in the final (thirteenth) month of home composting, whereas in the other two composters, the final moisture contents remained above the considered limit. Indeed, even the moisture content of compost products from different sources, commercially available and obtained from composting facilities, is reported to vary widely by up to 70% or more (Lasaridi et al., 2006; Boldrin et al., 2010). In general, an upper limitation to the moisture content of finished compost is required to avoid storage, transport, and handling difficulties (Krogmann et al., 2010); however, these aspects do not particularly affect the home composting approach because the obtained compost is expected to be used directly on the household garden or land (Andersen et al., 2011). Notably, the higher moisture contents in “comp-residential-p” composter compared with “comp-uni-u” composter, shown in Fig. 3 (upper diagram), in particular from the second to the eighth month of composting, could have contributed to the lower internal temperature regime in “comp-residential-p” composter (previously shown in Fig. 2 and Table 2). In fact, greater water content is indirectly expected to limit the internal temperature increase due to both a reduction in air-filled pores, which is detrimental to natural aeration, and a lower total dry mass of the filled heap, which is unfavorable to heat entrapment (Vallini et al., 1994; Karnchanawong and Suriyanon, 2011; Adhikari et al., 2013).

After a possible initial drop that most likely occurred during the first month of home composting (Karnchanawong and Suriyanon, 2011), the pH evolutions presented in the central diagram of Fig. 3 appear to be in qualitative agreement with the typically expected pH-time profile of the composting process (Tchobanoglous et al. 1993; Vallini et al., 1994). In particular, the experimental composters showed a similar temporal sequence with a phase of increasing pH (although varying from an intense, prolonged increase in “comp-residential-p” to a slighter, temporally limited increase in “comp-uni-u”) followed by a decreasing phase (although with a final increased value in the thirteenth month in “comp-rural-f” only). Except for the second month in “comp-rural-f” composter and the seventh to ninth months in “comp-residential-p” composter, the pH measures in the experimental composters evolved respecting the reference interval given in Table 1.

As shown in the lower diagram of Fig. 3, the measures of electrical conductivity in the experimental composters increased overall versus monthly composting time, except for the concentrated fluctuation in “comp-rural-f” composter between the fifth and seventh months of home composting. In general, the increase in electrical conductivity, which parametrically reflects the salinity of the matrix, is an additional indication of progress in the composting process as the gradual decomposition of organic matter is usually accompanied by the increased relative concentration of different mineral ions (Cáceres et al., 2006; Liu et al., 2011). By the thirteenth month of home composting, only the electrical conductivity measure in “comp-rural-f” composter remained greater than 5 dS m^{-1}, the value indicated in Epstein (2011) as an upper threshold above which potential phytotoxicity can occur. However, this phytotoxic behavior may be of concern especially in the specific application of compost as potting material, if used undiluted or in large amounts in potting mixtures (Manios, 2004; Lasaridi et al., 2006). Moreover, even analyzed commercial compost products had high electrical conductivity values, from 6 to over 12 dS m^{-1} (Lasaridi et al., 2006).

3.1.3. Temporal evolutions of organic carbon, C/N, total nitrogen, phosphorus, and potassium

Fig. 4 shows the resulting temporal evolutions of organic carbon (upper diagram), C/N ratio (central diagram), and total nitrogen (lower diagram) in the monitored experimental composters. For organic carbon (upper diagram of Fig. 4), the experimental composters exhibited overall decreases in measured contents versus monthly composting time, reflecting the progressive decomposition of organic matter by the microbial community (Andersen et al., 2011; Liu et al., 2011). The measured contents of organic carbon shown in the upper diagram of Fig. 4 evolved respecting the lower limit of Table 1, with the exception of the final content in “comp-rural-f” composter, which was just below the considered limit.

The central diagram of Fig. 4 shows that the initially measured C/N values (in the seventh monitoring month) in two experimental composters (i.e., “comp-uni-u” and “comp-house-u”) were greater than 30 to 40, above which the technical-scientific literature indicates the possibility of slowing the composting process (Vallini et al., 1994; Diaz et al., 2002; Krogmann, et al. 2010). Conversely, the initially measured C/N values (in the sixth monitoring month) in “comp-residential-p” and “comp-rural-f” remained lower compared with the previous composters. This variation in the initially measured C/N values in the experimental composters probably reflects the variety of components with differing C/N characteristics present in the categories of kitchen and garden/land wastes. Effectively, garden/land waste materials include either relatively high C/N ratio types (such as straw, leaves, barks, and shrub trimmings) or relatively low C/N ratio types (such as grass clippings, tree trimmings, mixed grasses, and farmyard manure); similarly, either relatively high C/N ratio types (such as fruit residues, potatoes, cooked meat scraps, and egg shells) or relatively low C/N ratio types (such as vegetable scraps, bread, fish scraps, and coffee grounds) occur among kitchen waste materials (Day and Shaw, 2001; Samples and Nash, 2001; Diaz et al., 2002; Niessen, 2002; Khan, 2009; Deublein and Steinhauser, 2011). Anyway, Fig. 4 (central diagram) shows that the C/N measures of the respective experimental composters more or less clearly decreased overall versus monthly composting time, which is qualitatively consistent with the gradual C/N reduction generally expected in the evolution of the composting process (Vallini et al., 1994; Day and Shaw, 2001; Diaz and Savage, 2007). As further shown in the central diagram of Fig. 4, by the end of experimental composting, the C/N measures in all of the monitored composters respected the corresponding upper limit given in Table 1.

For total nitrogen (lower diagram of Fig. 4), the experimental composters exhibited more or less pronounced overall increases in measured contents versus monthly composting time, with final values (in the thirteenth month) well above the corresponding lower limit given in Table 1. This increasing nitrogen condition appears in agreement with the concentration effect that is generally expected in the composting process due the gradual decomposition of organic matter, which causes a weight loss and, consequently, a relative increase in concentration (in terms of dry matter) provided that a possible concurrent nitrogen loss is relatively less than the weight loss (Saviozzi et al., 2004; Boldrin et al., 2010; Stentiford and de Bertoldi, 2010).

With final regard to extractable phosphorus and potassium, the temporal evolutions in the experimental composters are reported in Fig. 5. As shown in the left diagram of Fig. 5, two of the experimental composters (i.e., “comp-hilly-u” and “comp-house-u”) exhibited overall increases in measured P_2O_5 contents versus monthly composting time, with final values (in the thirteenth month) well above the lower limit given in Table 1. In the remaining experimental composters (i.e., "comp-residential-p" and "comp-rural-f"), the respective measured P_2O_5 contents, shown in the left diagram of Fig. 5, had only a limited variation during the composting time, evolving almost horizontally below the considered lower limit. In the right diagram of Fig. 5, the K_2O contents measured in "comp-uni-u" and "comp-house-u" composters increased overall versus monthly composting time and were constantly greater than the lower limit given in Table 1. Differently, the K_2O contents measured in "comp-residential-p" composter during the composting time remained just below or at the considered lower limit, whereas K_2O contents in "comp-rural-f" evolved by barely crossing the considered lower limit, presenting in particular a final value (in the thirteenth month) just above the limit and greater than the initially monitored value (in the sixth month). In effect, these resulting diversified behaviors are indicative of observable changes in the phosphorus and potassium contents during a composting process that can vary from increasing to decreasing over time (Adler and Sikora, 2004; Lin, 2008; Irshad et al., 2013), depending upon whether the prevailing condition concerns with the concentration effect due to the progressive decomposition of organic matter or alternately with the possible reduction of extractable phosphorus and potassium due to leaching losses (which, particularly for phosphate, may be favored by the presence of humified organic matter that masks or occupies possible matrix sorption sites) and/or due to transformation towards more stable forms (Bhatti et al., 1998; Traoré et al., 1999; Sommer, 2001; Boldrin et al., 2010). Anyway, the final P_2O_5 contents (in the thirteenth month) in three experimental composters (i.e., "comp-uni-u", "comp-house-u", and "comp-residential-p") were within the very wide interval 0.22-23.36% dm found in an array of analyzed compost products of different origins (Crippa and Corti, 1998), whereas the final P_2O_5 content in "comp-rural-f" composter remained just at the lower limit of this interval. Moreover, the final K_2O contents (in the thirteenth month) in all experimental composters were within the interval 0.08-4.93% dm found in the aforementioned array of compost products (Crippa and Corti, 1998).

3.1.4. Final evaluation of humification conditions and heavy metal contents

Regarding the humification conditions in the monitored experimental composters in the final (thirteenth) month of home composting, Fig. 6 displays the resulting values of humified organic carbon (left diagram) and HR (right diagram). The left diagram of Fig. 6 shows that the humified organic carbon contents detected in all of the experimental composters were greater than the lower limit given in Table 1. A pairwise evaluation of the final HR values in the right diagram of Fig. 6 indicates that higher values were reached in "comp-residential-p" and "comp-rural-f" compared with "comp-uni-u" and "comp-house-u" composters. As the humification rate is proportional to the progress of humification and hence of the stabilization of organic matter during composting (Tomati et al., 1995; Madejon et al., 1998), the lower HR values that finally characterized "comp-uni-u" and "comp-house-u" composters appear consistent with the slowing of the composting process that likely occurred in these two composters due to their high C/N values that were revealed in the initial monitoring month (as observed in the central diagram of Fig. 4 and outlined in Subsection 3.1.3).

Referring to heavy metals, Table 3 shows that the measured contents in the final (thirteenth) month were well below the respective limits of Table 1 in all experimental composters. These restricted levels confirm the importance of performing and controlling the source segregation of biowaste for any composting approach, including the home variant considered in this study, to minimize detrimental compost contamination by potentially toxic inorganic elements (Hogg et al., 2002; Smith, 2009; Barrena et al., 2014).

3.1.5. Modeling of temporal decreases and increases in parameters

Table 4 shows the resulting rate constants and coefficients of determination (R^2) for the first-order decrease modeling of moisture, organic carbon, and C/N measures in the experimental composters, with corresponding curve fits drawn in the respective diagrams of Fig. 3 (moisture) and

Fig. 4 (organic carbon and C/N). Notably, a pairwise evaluation of the rate constant results for organic carbon in Table 4 highlights the lower values in “comp-uni-u” and “comp-house-u” compared with “comp-residential-p” and “comp-rural-f” composters, thus indicating a slower organic matter decomposition process in “comp-uni-u” and “comp-house-u” composters because a lower k value in a first-order decreasing kinetics implies more time taken to complete a definite reduction fraction (Kuo, 1999; Niessen, 2002; In et al., 2007). This resulting condition appears consistent with both the high C/N values revealed in the initial monitoring month in “comp-uni-u” and “comp-house-u” composters (as shown in the central diagram of Fig. 4 and outlined in Subsection 3.1.3) and the lower HR values finally obtained in these composters (as shown in the right diagram of Fig. 6 and outlined in Subsection 3.1.4). Interestingly, the C/N modeling based on Eq. (1) in “comp-rural-f” and “comp-residential-p” composters also gave the estimated starting ratio values (as $P_{m,0}$) of 20.59 and 19.13, respectively. Thus, the starting C/N conditions were estimated to be either greater than the range from 15 to 20 (in “comp-uni-u” and “comp-house-u”, which were already greater in the seventh month) or essentially within this range (in “comp-rural-f” and “comp-residential-p”), representing in the technical-scientific literature a relevant threshold below which only a partial nitrogen loss through ammonia volatilization or nitrous oxide emission can be generally expected (Vallini et al., 1994; Diaz et al., 2002; Diaz and Savage, 2007). The lower moisture decrease rate constant shown in Table 4 in “comp-house-u” compared with the other composters, which indicates the comparative need for more time to obtain a definite reduction fraction in moisture (Kuo, 1999; Niessen, 2002), could have been influenced by the prolonged time of fresh biowaste feeding operations in this composter only (Tomati et al., 1995).

Table 5 shows the resulting rate constants (as line slopes) and R^2 for the zero-order increase modeling of the experimental measures of electrical conductivity, total nitrogen, P_2O_5, and K_2O, with corresponding straight-line fits drawn in the respective diagrams of Fig. 3 (electrical conductivity), Fig. 4 (total nitrogen), and Fig. 5 (phosphorus and potassium). Table 5 does not list a zero-order increase model for P_2O_5 and K_2O in “comp-residential-p” composter and for P_2O_5 in "comp-rural-f" composter because the respective R^2 values were close to zero, so that the related values of the correlation coefficient indicated a negligible or weak linear relationship between the parametrical measures and the monitoring time (Giudici, 2003; Hebel and McCarter, 2012), thus evidencing nearly horizontal patterns (Motulsky and Christopoulos, 2004). Notably, a pairwise evaluation of the slope values for electrical conductivity in Table 5 highlights that lower slopes characterized "comp-rural-f" and "comp-residential-p" compared with "comp-uni-u" and "comp-house-u" composters. This resulting condition appears qualitatively consistent with the nearly horizontal evolution in the P_2O_5 and K_2O measures in "comp-residential-p" composter and with the similarly horizontal evolution in the P_2O_5 measures and the limited increase in the K_2O measures in "comp-rural-f" composter (as shown in Fig. 5 and outlined in Subsection 3.1.3, and further confirmed by the aforementioned findings on R^2 and by the low k for potassium in "comp-rural-f" reported in Table 5). The probable occurrence of leaching losses (including phosphorus and potassium fractions) and/or formation of precipitated forms (comprehensive of Ca and Mg phosphates) (Traoré et al., 1999; Cáceres et al., 2006; Montemurro et al., 2009; Liu et al., 2011) can be supposed to have contributed to moderate the increases in soluble salt contents in "comp-rural-f" and "comp-residential-p" composters.

The modeled decreasing and increasing relationships, as related to the parameters of the individual experimental composters listed in Tables 4 and 5, were functional (with the exclusion of electrical conductivity) to identify the temporal conditions at which the respective reference limits of Table 1 can be met in home composting. As a visual result, Fig. 7 reports the identified temporal intervals of parametric compliances with the considered limits, which are marked either by lower (in case at zero) temporal bounds only (based on the possible combinations of parametric decrease and upper limit or, alternately, parametric increase and lower limit) or by both lower (at zero) and upper temporal bounds (with the further combination of parametric decrease and lower limit). A simple geometric evaluation of Fig. 7 shows that the double vertical lines, delimiting the time at 12-13 months, simultaneously intercept the solid horizontal lines and segments representing the various compliance conditions, with the exception of moisture in only two composters. Thus, the modeled parametric profiles in the experimental composters indicate 12-13 months as a suitable duration time for the home composting process to simultaneously meet typical reference limits, such as those assumed in Table 1, for parameters such as organic carbon, C/N, nitrogen, potassium, and phosphorus (although with the mentioned modeling evaluation limited to three and two experimental composters for the two last nutrients, respectively). The partial compliance with the moisture upper limit, achieved at 12-13 months in only two out of the four modeled composters, seems not particularly detrimental because the effects of moisture on the management of the final compost do not represent a major issue in the home composting approach (as previously noted in Subsection 3.1.2).

3.2. Controlled provincial composters

Concerning the two sub-sets of provincial composters, controlled in the seventh and fifteenth months of home composting, the diagrams of the obtained box-and-whisker plots are graphically combined as parametrical aggregations identical to those adopted in Figs. 3-6 and Table 3 for the monitored experimental composters. Thus, Fig. 8 first aggregates the resulting box-and-whisker plots for moisture (upper diagram), pH (central diagram), and electrical conductivity (lower diagram). Referring to moisture content in the upper diagram of Fig. 8, the boxes of quartiles for both sub-sets of provincial composters remained above the upper limit given in Table 1. Differently, the central diagram of Fig. 8 shows that all pH values in both sub-sets of provincial composters respected the reference interval given in Table 1. Finally, the lower diagram of Fig. 8 reveals that electrical conductivity had a higher median value in the sub-set of provincial composters controlled in the fifteenth month of home composting than the sub-set controlled in the seventh month, with a resulting relative difference of 33% (determined as $[(\text{median}_{15\ \text{months}} - \text{median}_{7\ \text{months}}) / (\text{median}_{7\ \text{months}})] \times 100$).

Fig. 9 then aggregates the resulting box-and-whisker plots for organic carbon (upper diagram), C/N (central diagram), and total nitrogen (lower diagram). In the upper diagram of Fig. 9, aside from the minimum value (an outlier) in the sub-set controlled in the fifteenth month, all measured organic carbon contents in both sub-sets of provincial composters were in compliance with the lower limit given in Table 1; in terms of central tendencies, the fifteenth month sub-set of provincial composters had a median value just below that of the seventh month, with the resulting relative difference (determined as $[(\text{median}_{7\ \text{months}} - \text{median}_{15\ \text{months}}) / (\text{median}_{7\ \text{months}})] \times 100$) limited to 2%. The upper limit given in Table 1 for C/N distinguished between the central tendencies shown in Fig. 9 (central diagram) by the two provincial sub-sets of C/N measures, as the corresponding median values remained unsatisfactorily above and satisfactorily below the limit in the seventh and fifteenth months, respectively; in particular, the relative difference between the median values was 16%. Concerning total nitrogen content, shown in the lower diagram of Fig. 9, the boxes of quartiles for both sub-sets of provincial composters remained satisfactorily above the lower limit given in Table 1; in terms of central tendencies, the sub-set in the fifteenth month presented a median value just above that in the seventh month, with the resulting relative difference limited to 4%.

Referring to phosphorus and potassium contents, the respective diagrams of Fig. 10 show that the boxes of quartiles for both nutrients and sub-sets of controlled provincial composters were above the corresponding lower limits given in Table 1.

Concerning the humification conditions, the left diagram of Fig. 11 shows that the boxes of quartiles for humified organic carbon in both sub-sets of provincial composters remained above the lower limit given in Table 1. Further, in the right diagram of Fig. 11, HR exhibited a higher median value in the sub-set of provincial composters controlled in the fifteenth month than that controlled in the seventh month, with a resulting relative difference of 30%.

Even examining distinct sub-sets of the controlled composters, the evident decrease in the median for C/N with increasing time from seven to fifteen months of home composting, as well as the evident increase in the same statistical measure for electrical conductivity and HR over the same increasing time, could be considered compatible with the character of parameters with expected decreasing or increasing evolutions, respectively, during the composting process. Due to the limited relative differences between the sub-sets of provincial composters (at seven and fifteen months), the comparison of the central tendency measures for organic carbon and nitrogen, in contrast, did not show similarly noticeable evidence of agreement with the expected parametric decrease or increase, respectively, during the composting process.

Further, in terms of data variability, parameters expected to decrease during the composting process, such as organic carbon, C/N, and moisture, were similarly characterized, respectively, in Fig. 9 (upper and central) and Fig. 8 (upper) by lower variability (indicated by a lower box height) in the sub-set of provincial composters controlled in the fifteenth month of home composting than that controlled in the seventh month. Differently, parameters expected to increase during the composting process, such as electrical conductivity, total nitrogen, and HR, were characterized by higher variability in the sub-set of provincial composters in the fifteenth month than that in the seventh month. This condition is observed, in particular, for nitrogen and HR by comparing the box heights in Fig. 9 (lower) and Fig. 11 (right), respectively, whereas for electrical conductivity, it appears in Fig. 8 (lower) as a slightly greater range (i.e., the difference between the maximum and minimum values, representing an alternative indicator of variability: Anderson and Finn, 1996; Giudici, 2003) in the fifteenth month compared with the seventh month. The box-and-whisker plot approach also provides visual information regarding the possible data asymmetry based on either the proportion between the two parts of the box (Anderson and Finn, 1996) or the comparison between the distances maximum-median and median-minimum (Kuehl et al., 2001); thus, total nitrogen, HR, and electrical conductivity were also similarly characterized by positively skewed data in both sub-sets of provincial composters. In particular, this condition is determined for total nitrogen (lower diagram in Fig. 9) and HR (right diagram in Fig. 11) from the greater distances between the upper quartile and median than between the median and lower quartile (Giudici, 2003), whereas for electrical conductivity (lower diagram in Fig. 8), the distances between the maximum and median were more or less clearly greater than the respective distances between the median and minimum (Kuehl et al., 2001). Reliably, these visual indications were further reflected by the positive values of the calculated asymmetry index (Giudici, 2003), which, although indicative of different degrees of positive skewness (Wegner, 2007), were precisely equal to 0.177 and 0.504 for electrical conductivity, 0.862 and 0.512 for nitrogen, and 1.156 and 1.582 for HR in the seventh and fifteenth months of home composting, respectively. Interestingly, the reduced variability of the parametric data with increased composting time, as revealed for moisture, organic carbon, and C/N when comparing the two sub-sets of controlled provincial composters, could be considered compatible with the nature of parameters expected to decrease over time, for which it can be supposed a progressive compaction of parametric values, with the bottom limitation on indefinite decreasing imposed by the asymptotic character of the representative first-order kinetic models. Similarly, the increased variability of the parametric data with increased home composting time, revealed by comparing the two provincial sub-sets of nitrogen, HR, and electrical conductivity data, in combination with the positive skewness of the data (thus presenting a longer tail of distribution towards the higher parametric values), both appear compatible with the alternative nature of parameters expected to increase over time, which are therefore unbounded on top during their evolution (von Hippel, 2011).

With regard to heavy metals, the box-and-whisker plots in Fig. 12 show that the resulting contents in the sub-set of composters controlled in the seventh month of home composting, displayed as quartiles, whiskers, and outliers, were below the respective upper limits of Table 1, with the exception of the upper whisker for cadmium because of two sampled composts with slightly higher contents than the considered limit. The higher cadmium values could most likely be connected either with metallic fragments discarded accidentally into the composters or with waste papers and cardboards entering the home composting process, considering in the latter case the possible presence of cadmium in printing inks or even in the printing and decoration on the outside of wrapping papers and cardboards used for food-related purposes (Zorzi and Pinamonti, 1998; Reilly, 2002; Smith and Jasim, 2009). Finally, *Salmonella* was not detected in any compost sample from the sub-set of provincial composters in the seventh month, thereby satisfying the regulatory requirement of absence for sanitary safety (Table 1).

Given the temporal discriminant for C/N only in Fig. 9 (central), the comparison between the two controlled sub-sets of provincial composters specifically indicates 15 months as a duration time of home composting at which the central tendency measures for pH, organic carbon, nitrogen, humified organic carbon, phosphorous, potassium, and the mentioned C/N are expected to all simultaneously meet their respective limits (such as those in Table 1) typically assumable for compost. Indeed, moisture remains outside this simultaneous condition of adequacy with the parametric requirements, which is in line with the partial compliance at the suitable duration time identified in the simulations of Fig. 7 on the monitored experimental composters.

4. Conclusions

The objective of the present study was to contribute to the technical-scientific knowledge regarding the process evolution and compost quality that can be expected and obtained, respectively, in the decentralized approach of home composting.

In spite of the intrinsic simplicity of this approach, and although the registered temperature profiles (in “comp-residential-p” and “comp-uni-u” composters) indicated that diversified regimes could occur even in identically shaped composting units, the process monitoring of the four experimental composters showed overall decreasing profiles versus composting time for parameters such as moisture (with the exception of only the initial monitoring months in two composters), organic carbon, and C/N, as well as overall increasing profiles for parameters such as electrical conductivity and total nitrogen. These evolutions represented reliable qualitative indications of progress in the composting process. Appropriate comparative evaluations of parametric measures and modeled kinetics in the monitored experimental composters also indicated the plausibility of the following interactions in home composting: (1) initially high C/N values were reasonably associated with lower organic matter decomposition rates and lower final humification levels (as revealed by comparing the pairs of “comp-uni-u”-“comp-house-u” and “comp-residential-p”-“comp-rural-f”); (2) higher moisture contents presumably contributed to restrain the internal temperature regime (as supposed from comparing “comp-residential-p” and “comp-uni-u”); (3) nearly horizontal or slightly increasing evolutions of extractable phosphorus and potassium contents were reasonably associated with lower slopes of increase in electrical conductivity (as revealed by comparing the pairs of “comp-residential-p”-“comp-rural-f” and “comp-uni-u”-“comp-house-u”); and (4) a prolonged time of biowaste additions presumably contributed to a lower rate of decrease in moisture (as supposed from comparing “comp-house-u” with the other composters).

The sub-sets of controlled provincial composters had a noticeable decrease in the central tendency measure (given by the median) of C/N from seven to fifteen months of home composting, as well as noticeable increases in the medians of electrical conductivity and HR over the same time period, which, as comparative conditions, appear compatible with the respective parametric decreasing or increasing evolutions generally expected in the composting process. In terms of the parametric data variability in the two sub-sets of controlled composters, the decreases in the corresponding measure (given by the IQR) for moisture, organic carbon, and C/N from seven to fifteen months of composting, as well as the increases in IQR (or the alternative range measure) for total nitrogen, HR, and electrical conductivity over the same time period, can be explained again by the expected decreasing or increasing evolutions during the composting process. Further, electrical conductivity, total nitrogen, and HR data were characterized in both sub-sets of controlled composters by a similarly interpretable condition of positive skewness.

The modeled parametric kinetics in the monitored experimental composters (with the exception of potassium and phosphorus in one and two composters, respectively), in combination with the evaluation of the parametric central tendencies in the sub-sets of controlled provincial composters, all indicate a suitable duration time for home composting of between 12 and 15 months, at which the simultaneous compliance with compost limits typically adoptable for parameters, such as pH, organic carbon, C/N, nitrogen, humified organic carbon, phosphorus and potassium, can be expected. Further, at this indicated duration time, full compliance with typical upper limits on heavy metals is also expected (as shown in the monitored experimental composters), provided that careful attention is paid to avoid the inappropriate addition of metal fragments or even metal containing materials to the composters (as is supposed to have occurred for Cd in two samples of the sub-set of provincial composters controlled in the seventh month of home composting). The difficulty in simultaneously meeting an upper limitation on moisture seems to not be a relevant issue in home composting, given the expected use of the produced compost directly on-site. Ideally, the derived duration time of 12-15 months places the decentralized home composting approach near the upper limit of the total duration time (from 2 to 12 months) generally expected in the simplest of centralized composting approaches (i.e., the windrow process) (Bidlingmaier and Papadimitriou, 2000). Moreover, this derived suitable time seems to fit well with the prevalent attitude of households in terms of their actual length of time using home composters (i.e., over 12 months, according to the survey by Curtis et al., 2009).

Acknowledgements

This study was supported by the Province of Pesaro-Urbino (Marche Region, Italy), including two undergraduate grants. Dr. E. Cecchini and her team at the Department “Environment, Agriculture, Renewable Energy, and Environmental Planning” of the Province of Pesaro-Urbino provided fruitful cooperation. The authors thank Mr. P. Paolucci at the Meteorological Observatory “Serperi” of the University of Urbino “Carlo Bo” and Dr. A. Casagrande at the Meteorological Web-Site Section of the Province of Pesaro-Urbino for providing the ambient temperature data. The authors also thank the staff at the Environmental Chemistry Laboratory and the Toxicological and Hygienic Science Laboratory of the University of Urbino “Carlo Bo” for their cooperation and assistance.

References

Adhikari, B.K., Trémier, A., Martinez, J., Barrington, S., 2010. Home and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada. Waste Management and Research 28, 1039-1053.

Adhikari, B.K., Trémier, A., Barrington, S., Martinez, J., Daumoin, M., 2013. Gas emissions as influenced by home composting system configuration. Journal of Environmental Management 116, 163-171.

Adler, P.R., Sikora, L.J., 2004. Composting fish manure from aquaculture operations. BioCycle November, 62-66.

Amlinger, F., Peyr, S., Cuhls, C., 2008. Greenhouse gas emissions from composting and mechanical biological treatment. Waste Management and Research 26, 47-60.

Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2010. Greenhouse gas emissions from home composting of organic household waste. Waste Management 30, 2475-2482.

Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2011. Mass balances and life cycle inventory of home composting of organic waste. Waste Management 31, 1934-1942.

Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2012. Home composting as an alternative treatment option for organic household waste in Denmark: An environmental assessment using life cycle assessment-modeling. Waste Management 32, 31-40.

Anderson, T.W., Finn, J.D., 1996. The new statistical analysis of data. Springer-Verlag, New York, USA.

ANPA (National Environment Protection Agency), 2001. Analytical methods of compost. Handbook and standard series no. 3/2001, Rome, Italy (in Italian).

Barrena, R., Font, X., Gabarrell, X., Sánchez, A., 2014. Home composting versus industrial composting: Influence of composting system on compost quality with focus on compost stability. Waste Management 34, 1109-1116.

Bhatti, J.S., Comerford, N.B., Johnston, C.T., 1998. Influence of oxalate and soil organic matter on sorption and desorption of phosphate onto a spodic horizon. Soil Science Society of America

Journal 62, 1089-1095.

Bidlingmaier, W., Papadimitriou, E.K., 2000. Recovery of organics: Composting and anaerobic digestion. In: Innovation in waste management, Proceedings of the IV European waste forum organized by EWC (European Waste Club), Environmental Series, volume 23/b, CIPA Publisher, Milan, Italy, pp. 3-22.

Boldrin, A., Christensen, T.H., Körner, I., Krogmann, U., 2010. Composting: Mass balances and product quality. In: Christensen, T.H. (Ed.), Solid waste technology & management, volume 2, John Wiley & Sons, Ltd, Chichester, UK, pp. 569-582.

Cáceres, R., Flotats, X., Marfà, O., 2006. Changes in the chemical and physicochemical properties of the solid fraction of cattle slurry during composting using different aeration strategies. Waste Management 26, 1081-1091.

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. Resources, Conservation and Recycling 54, 893-904.

Council Directive 1999/31/EC on the landfill of waste. Official Journal of the European Communities, L 182/1-19, 16.07.1999.

Cox, J., Giorgi, S., Sharp, V., Strange, K., Wilson, D.C., Blakey, N., 2010. Household waste prevention - A review of evidence. Waste Management and Research 28, 193-219.

Crippa, L., Corti, L., 1998. Chemical characteristics of compost products and growing media. In: Genevini, P.L. (Ed.), Compost and agriculture, Fondazione Lombardia per l'Ambiente Publisher, Milan, Italy, pp. 203-244 (in Italian).

Curtis, A., Phillips, P.S., Tudor, T., 2009. Driving sustainable waste management in Northern Ireland - Home composting of green garden waste in Castlereagh. The Journal of Solid Waste Technology and Management 35, 191-199.

Day, M., Shaw, K., 2001. Biological, Chemical, and Physical Processes of Composting. In: Stoffella, P.J., Kahn, B.A. (Eds.), Compost utilization in horticultural cropping systems, CRC

Press, Boca Raton, USA, pp. 17-50.

de Bertoldi, M., Civilini, M., Comi, G., 1990. MSW compost standards in the European Community. BioCycle August, 60-62.

Deublein, D., Steinhauser, A., 2011. Biogas from waste and renewable resources: An introduction. Second, revised and expanded edition, Wiley-VCH Verlag, Weinheim, Germany.

Diaz, L.F., Savage, G.M., Gouleke, C.G., 2002. Composting of municipal solid wastes. In: Tchobanoglous, G., Kreith, F. (Eds.), Handbook of solid waste management, second edition, Mc-Graw Hill, Inc., New York, USA, pp. 12.1-12.70.

Diaz, L.F., Savage, G.M., 2007. Factors that affect the process. In: Diaz, L.F., de Bertoldi, M., Bidlingmaier, W., Stentiford, E. (Eds.), Compost science and technology, Elsevier, Oxford, UK, pp. 49-65.

Directive 2008/98/EC on waste and repealing certain directives. Official Journal of the European Union, L 312/3-30, 22.11.2008.

Epstein, E., 2011. Industrial composting: Environmental engineering and facilities management. CRC Press, Boca Raton, USA.

Ermolaev, E., Sundberg, C., Pell, M., Jönsson, H., 2014. Greenhouse gas emissions from home composting in practice. Bioresource Technology 151, 174-182.

European Commission, 2005. Taking sustainable use of resources forward: A thematic strategy on the prevention and recycling of waste. COM(2005) 666 final, Brussels, Belgium.

European Commission, 2006. Commission decision of 3 November 2006 establishing revised ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to soil improvers (2006/799/EC). Official Journal of the European Union, L 325/28-34, 24.11.2006.

European Commission, 2010. Communication from the Commission to the Council and the European Parliament on future steps in bio-waste management in the European Union. COM(2010)235 final, Brussels, Belgium.

Giudici, P., 2003. Applied data mining: Statistical methods for business and industry. John Wiley & Sons, Ltd, Chichester, UK.

Hebel, J.R., McCarter, R.J., 2012. A study guide to epidemiology and biostatistics. Seventh edition, Jones & Bartlett Learning, Burlington, USA.

Hogg, D., Barth, J., Favoino, E., Centemero, M., Caimi, V., Amlinger, F., Devliegher, W., Brinton, W., Antler, S., 2002. Comparison of compost standards within the EU, North America and Australasia. Main report, published by the Waste and Resources Action Programme (WRAP), Banbury, UK.

In, B.H., Park, J.S., Namkoong, W., Kim, J.D., Ko, B.I., 2007. Effect of sewage sludge mixing ratio on composting of TNT-contaminated soil. Journal of Industrial and Engineering Chemistry 13, 190-197.

Irshad, M., Eneji, A.E., Hussain, Z., Ashraf, M., 2013. Chemical characterization of fresh and composted livestock manures. Journal of Soil Science and Plant Nutrition 13, 115-121.

Italian Ministry of Agriculture and Forestry, 2000. Chemical analytical methods of soil. Edited by the National Committee for Pedology and Soil Quality in cooperation with the International Union of Soil Sciences and the Italian Society of Soil Science, Series of Agricultural Analytical Methods, Franco Angeli Publisher, Milan, Italy (in Italian).

Karnchanawong, S., Suriyanon, N., 2011. Household organic waste composting using bins with different types of passive aeration. Resources, Conservation and Recycling 55, 548-553.

Khan, B.H., 2009. Non-conventional energy resources. Second edition, Tata McGraw Hill Education, New Delhi, India.

Krogmann, U., Körner, I., Diaz, L.F., 2010. Composting: Technology. In: Christensen, T.H. (Ed.), Solid waste technology & management, volume 2, John Wiley & Sons, Ltd, Chichester, UK, pp. 533-568.

Kuhad, R.C., Chandna, P., Singh, A., 2011. Composting of lignocellulosic waste material for soil amendment. In: Singh, A., Parmar, N., Kuhad, R.C. (Eds.), Bioaugmentation, biostimulation and biocontrol, Soil Biology Series, volume 28, Springer, Heidelberg, Germany, pp. 107-128.

Kuehl, R.O., McClaran, M.P., Van Zee, J., 2001. Detecting fragmentation of cover in desert grasslands using line intercept. Journal of Range Management 54, 61-66.

Kuo, J., 1999. Practical design calculations for groundwater and soil remediation. Lewis Publishers, Boca Raton, USA.

Lasaridi, K., Protopapa, I., Kotsou, M., Pilidis, G., Manios, T., Kyriacou, A., 2006. Quality assessment of composts in the Greek market: The need for standards and quality assurance. Journal of Environmental Management 80, 58-65.

Legislative Decree No. 75/2010. Revision and updating of the fertilizer legislation. Ordinary Annex of the Official Italian Gazette No. 106/L, 26.05.2010 (in Italian).

Lin, C., 2008. A negative-pressure aeration system for composting food wastes. Bioresource Technology 99, 7651-7656.

Liu, D., Zhang, R., Wu, H., Xu, D., Tang, Z., Yu, G., Xu, Z., Shen, Q., 2011. Changes in biochemical and microbiological parameters during the period of rapid composting of dairy manure with rice chaff. Bioresource Technology 102, 9040-9049.

Madejón, E., Galli, E., Tomati, U., 1998. Composting of wastes produced by low water consuming olive mill technology. Agrochimica 42, 135-146.

Manios, T., 2004. The composting potential of different organic solid wastes: Experience from the island of Crete. Environment International 29, 1079-1089.

Martínez-Blanco, J., Colón, J., Gabarrell, X., Font, X., Sánchez, A., Artola, A., Rieradevall, J., 2010. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30, 983-994.

McKinley, S., Williams, I.D., 2007. Assessing the environmental impacts of home composting. In: Cossu, R., Diaz, L.F., Stegmann, R. (Eds.), Proceedings “Sardinia 2007, eleventh international waste management and landfill symposium”, CISA (Environmental Sanitary Engineering Centre) Publisher, Padua, Italy.

Ministerial Decree No. 10.07.2013. Updating of the annexes of the Legislative Decree No. 75/2010 on fertilizers. Official Italian Gazette No. 218, 17.09.2013 (in Italian).

Montemurro, F., Diacono, M., Vitti, C., Debiase, G., 2009. Biodegradation of olive husk mixed with other agricultural wastes. Bioresource Technology 100, 2969-2974.

Motulsky, H., Christopoulos, A., 2004. Fitting models to biological data using linear and nonlinear regression: A Practical guide to curve fitting. GraphPad Software Inc. and Oxford University Press, New York, USA.

Niessen, W.R., 2002. Combustion and incineration processes. Third edition, Marcel Dekker, Inc., New York, USA.

Onida, M., 2000. Innovation in prevention of quantitative and qualitative waste production. In: Innovation in waste management, Proceedings of the IV European waste forum organized by EWC (European Waste Club), Environmental Series, volume 23/a, CIPA Publisher, Milan, Italy, pp. 91-105.

Reilly, C., 2002. Metal contamination of food: Its significance for food quality and human health. Third edition, Blackwell Science Ltd, Oxford, UK.

Resolution No. 27.07.1984. Indications for the first application of art. 4 of Law 915/1982 on waste disposal. Ordinary Annex of the Official Italian Gazette No. 253, 13.09.1984 (in Italian).

Ryckeboer, J., Mergaert, J., Coosemans, J., Deprins, K., Swings, J., 2003. Microbiological aspects of biowaste during composting in a monitored compost bin. Journal of Applied Microbiology 94, 127-137.

Samples, T., Nash, M.A., 2001. Composting yard, garden and food wastes at home. The University of Tennessee Agricultural Extension Service Publication, PB 1479, Knoxville, USA.

Saviozzi, A., Cardelli, R., Levi-Minzi, R., Riffaldi, R., 2004. Evolution of biochemical parameters during composting of urban wastes. Compost Science & Utilization 12, 153-160.

Sharp, V., Giorgi, S., Wilson, D.C., 2010. Delivery and impact of household waste prevention intervention campaigns (at the local level). Waste Management and Research 28, 256-268.

Smith, S.R., 2009. A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environment International 35, 142-156.

Smith, S.R., Jasim, S., 2009. Small-scale home composting of biodegradable household waste: Overview of key results from a 3-year research programme in West London. Waste Management and Research 27, 941-950.

Sommer, S.G., 2001. Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. European Journal of Agronomy 14, 123-133.

Stentiford, E., de Bertoldi, M., 2010. Composting: Process. In: Christensen, T.H. (Ed.), Solid waste technology & management, volume 2, John Wiley & Sons, Ltd, Chichester, UK, pp. 515-532.

Tchobanoglous, G., Theisen, H., Vigil, S., 1993. Integrated solid waste management: Engineering principles and management issues. McGraw-Hill, Inc., New York, USA.

Tomati, U., Galli, E., Pasetti, L., Volterra, E., 1995. Bioremediation of olive-mill wastewaters by composting. Waste Management and Research 13, 509-518.

Traoré, O., Sinaj, S., Frossard, E., Van De Kerkhove, J.M., 1999. Effect of composting time on phosphate exchangeability. Nutrient Cycling in Agroecosystems 55, 123-131.

Tucker, P., Speirs, D., Fletcher, S.I., Edgerton, E., McKechnie, J., 2003. Factors affecting take-up of and drop-out from home composting schemes. Local Environment 8, 245-259.

Vallini, G., Pera, A., Valdrighi, M., 1994. Aerobic biostabilization of organic substrates: Microbial ecology and biotechnology of composting process. In: de Fraja Frangipane, E. (Ed.), Engineering of composting, Environment Series, volume 6, CIPA Publisher, Milan, Italy, pp. 83-109 (in Italian).

von Hippel, P., 2011. Skewness. In: Lovric, M. (Ed.), International encyclopedia of statistical science, Springer Verlag, Berlin, Heidelberg, Germany, pp. 1340-1342.

Wegner, T., 2007. Applied business statistics: Methods and Excel-based applications. Second edition, Juta & Co. Ltd, Cape Town, South Africa.

Zorzi, G., Pinamonti, F. 1998. Compost quality requirements and agricultural use. In: de Fraja

Frangipane, E., Vismara, R., (Eds.), Material and energy recovery from solid waste, Environment Series, volume 19, CIPA Publisher, Milan, Italy, pp. 223-260 (in Italian).

Zurbrügg, C., Drescher, S., Patel, A., Sharatchandra, H.C., 2004. Decentralized composting of urban waste - an overview of community and private initiatives in Indian cities. Waste Management 24, 655-662.

Table 1

Parametric reference limits considered in this study for the monitoring and quality control of the home composting process.

Parameter	Limit	Regulation
Moisture (%, w/w)	≤ 50	Legislative Decree No. 75/2010
pH	6-8.8	Ministerial Decree No. 10.07.2013
Organic carbon (% dm)	≥ 20	Legislative Decree No. 75/2010
Humified organic carbon - HA + FA (% dm)	≥ 7	Legislative Decree No. 75/2010
C/N	≤ 25	Legislative Decree No. 75/2010
Total nitrogen (% dm)	> 1	Resolution No. 27.07.1984
Phosphorus (as P_2O_5) (% dm)	> 0.5	Resolution No. 27.07.1984
Potassium (as K_2O) (% dm)	> 0.4	Resolution No. 27.07.1984
Cadmium (mg kg^{-1} dm)	≤ 1.5	Legislative Decree No. 75/2010
Chromium (mg kg^{-1} dm)	< 100	Eco-label to soil improvers (2006/799/EC)
Copper (mg kg^{-1} dm)	≤ 230	Legislative Decree No. 75/2010
Lead (mg kg^{-1} dm)	≤ 140	Legislative Decree No. 75/2010
Nickel (mg kg^{-1} dm)	≤ 100	Legislative Decree No. 75/2010
Zinc (mg kg^{-1} dm)	≤ 500	Legislative Decree No. 75/2010
Salmonella (cfu 25 g^{-1})	absent	Legislative Decree No. 75/2010

dm: dry matter.

Table 2

Statistical measures for the monitored temperature profiles of “comp-uni-u” and “comp-residential-p” composters (see Fig. 2).

Temperature parameter	No. of data	Min (°C)	Max (°C)	Mean (°C)	Median (°C)
“Comp-uni-u” composter					
$T_{internal}$	56	7.0	58.0	32.7	34.0
$T_{ambient\ air}$	214	- 0.3	28.3	15.9	16.9
$T_{internal}$ - $T_{ambient\ air}$	56	0.0	38.5	16.9	12.8
“Comp-residential-p” composter					
$T_{internal}$	132	14.0	38.0	26.4	26.5
$T_{ambient\ air}$	132	12.0	28.4	21.0	22.1
$T_{internal}$ - $T_{ambient\ air}$	132	0.2	13.1	5.4	5.2

Table 3

Monitored experimental composters: resulting heavy metal contents in the final (thirteenth) month of home composting.

Composter	Cd (mg kg^{-1} dm)	Cr (mg kg^{-1} dm)	Cu (mg kg^{-1} dm)	Ni (mg kg^{-1} dm)	Pb (mg kg^{-1} dm)	Zn (mg kg^{-1} dm)
Comp-uni-u	ND	27.50	7.71	1.56	11.90	8.80
Comp-house-u	ND	ND	8.53	2.60	14.60	66.60
Comp-residential-p	0.40	34.00	26.71	1.12	8.35	7.96
Comp-rural-f	0.08	22.00	33.49	ND	4.13	4.83
Upper limit (see Table 1)	1.5	100	230	100	140	500

ND: Not Detected (i.e., less than the limit of analytical detection).

Table 4

Monitored experimental composters: resulting rate constants and coefficients of determination for the first-order decrease modeling of moisture, organic carbon, and C/N measures.

Parameter	Composter	*k* (month^{-1})	R^2
Moisture	Comp-uni-u	0.033	0.877
	Comp-house-u	0.029	0.963
	Comp-residential-p	0.039	0.607
	Comp-rural-f	0.042	0.903
Organic carbon	Comp-uni-u	0.021	0.868
	Comp-house-u	0.028	0.945
	Comp-residential-p	0.040	0.880
	Comp-rural-f	0.056	0.957
C/N	Comp-uni-u	0.106	0.825
	Comp-house-u	0.116	0.850
	Comp-residential-p	0.098	0.860
	Comp-rural-f	0.073	0.786

Table 5

Monitored experimental composters: resulting rate constants and coefficients of determination for the zero-order increase modeling of electrical conductivity, nitrogen, phosphorus, and potassium measures.

Parameter	Composter	*k* (parameter unit month^{-1})	R^2
Electrical conductivity	Comp-uni-u	0.187	0.944
	Comp-house-u	0.251	0.944
	Comp-residential-p	0.171	0.890
	Comp-rural-f	0.159	0.447
Total nitrogen	Comp-uni-u	0.152	0.916
	Comp-house-u	0.173	0.973
	Comp-residential-p	0.153	0.732
	Comp-rural-f	0.056	0.445
P_2O_5	Comp-uni-u	0.258	0.858
	Comp-house-u	0.219	0.924
K_2O	Comp-uni-u	0.216	0.945
	Comp-house-u	0.160	0.908
	Comp-rural-f	0.017	0.327

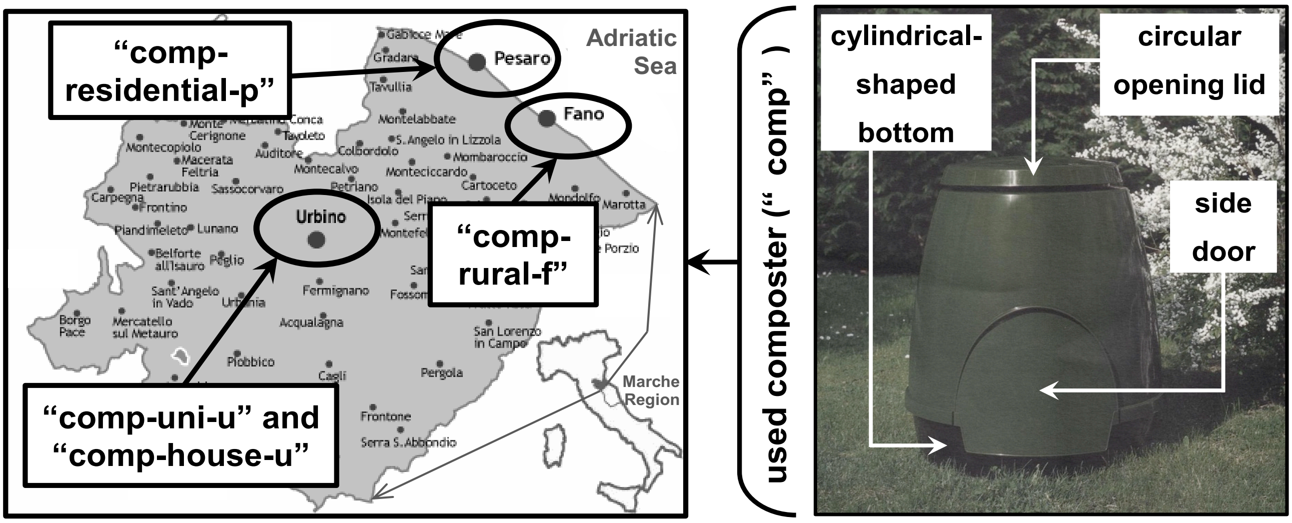

Fig. 1. Municipal locations of the monitored experimental composters (left), and representative picture of the composter used (right).

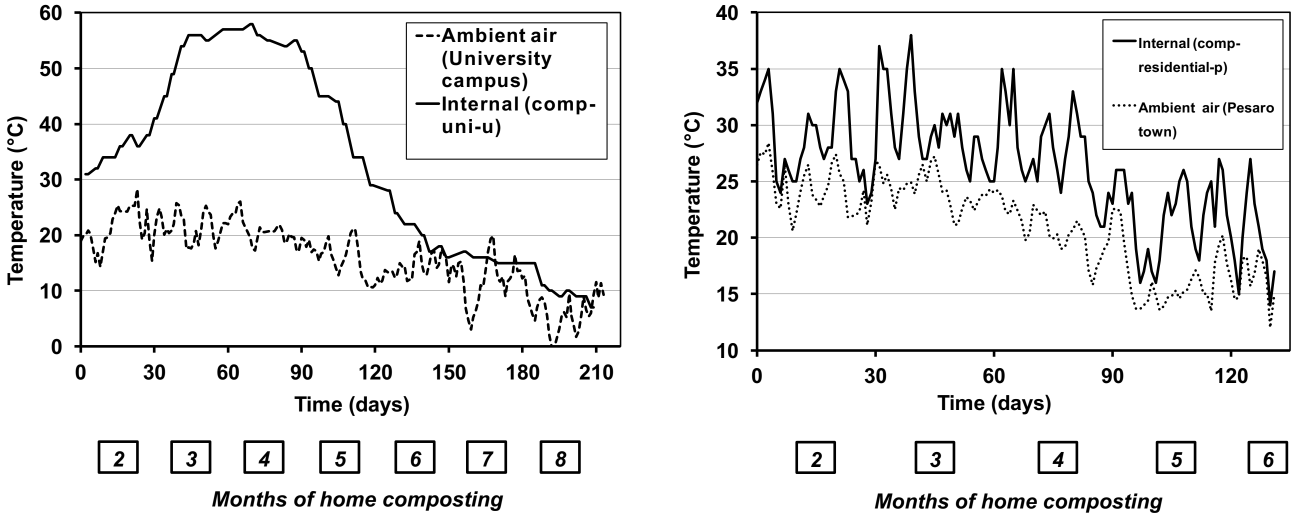

Fig. 2. Internal temperature profiles monitored in the experimental composters “comp-uni-u” (left) and “comp-residential-p” (right) in comparison with ambient temperature profiles. Temperature recording was performed from the second to the eighth month of home composting in “comp-uni-u” and from the second to the sixth month (first ten days) in “comp-residential-p”.

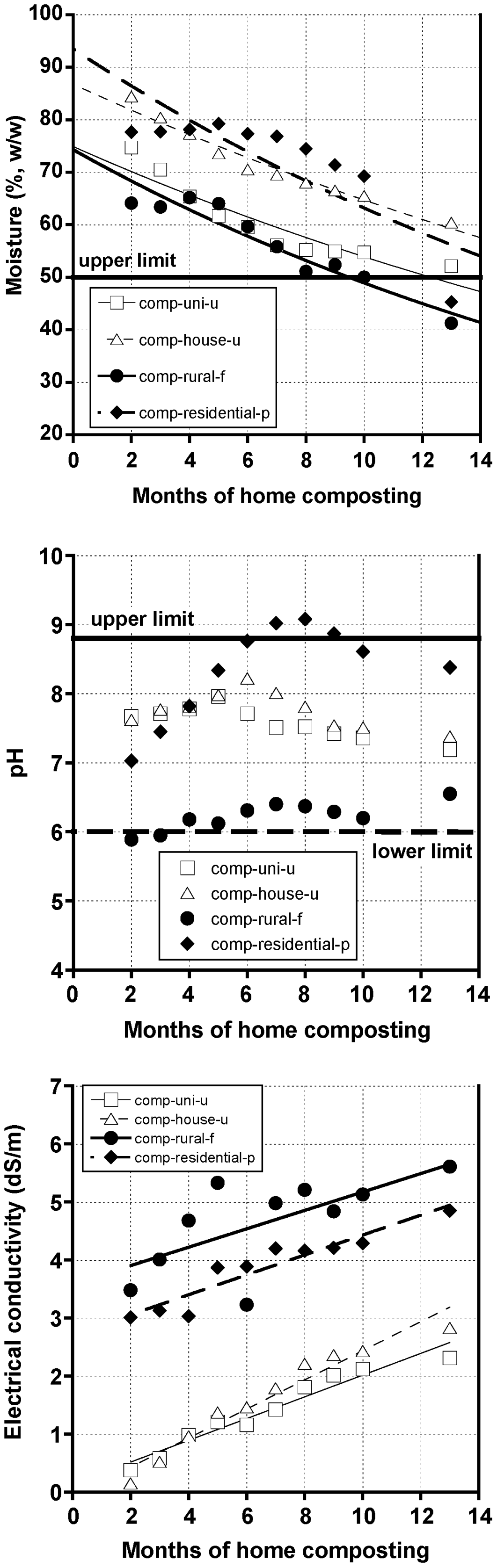

Fig. 3. Monitored experimental composters: temporal evolutions of moisture (upper), pH (central), and electrical conductivity (lower). Symbols represent the experimental measures, and lines represent the fitted models (first-order decrease for moisture and zero-order increase for electrical conductivity). For the adopted limits (horizontal lines) for moisture and pH, see Table 1.

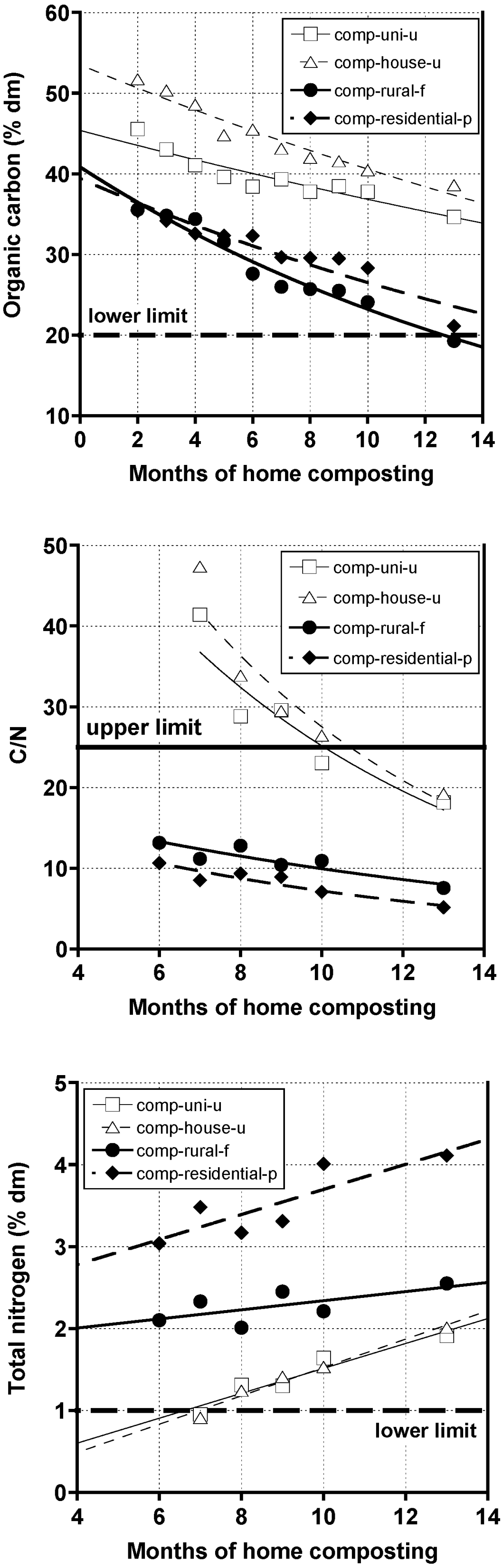

Fig. 4. Monitored experimental composters: temporal evolutions of organic carbon (upper), C/N (central), and total nitrogen (lower). Symbols represent the experimental measures, and lines represent the fitted models (first-order decrease for organic carbon and C/N and zero-order increase for total nitrogen). For the adopted limits (horizontal lines), see Table 1.

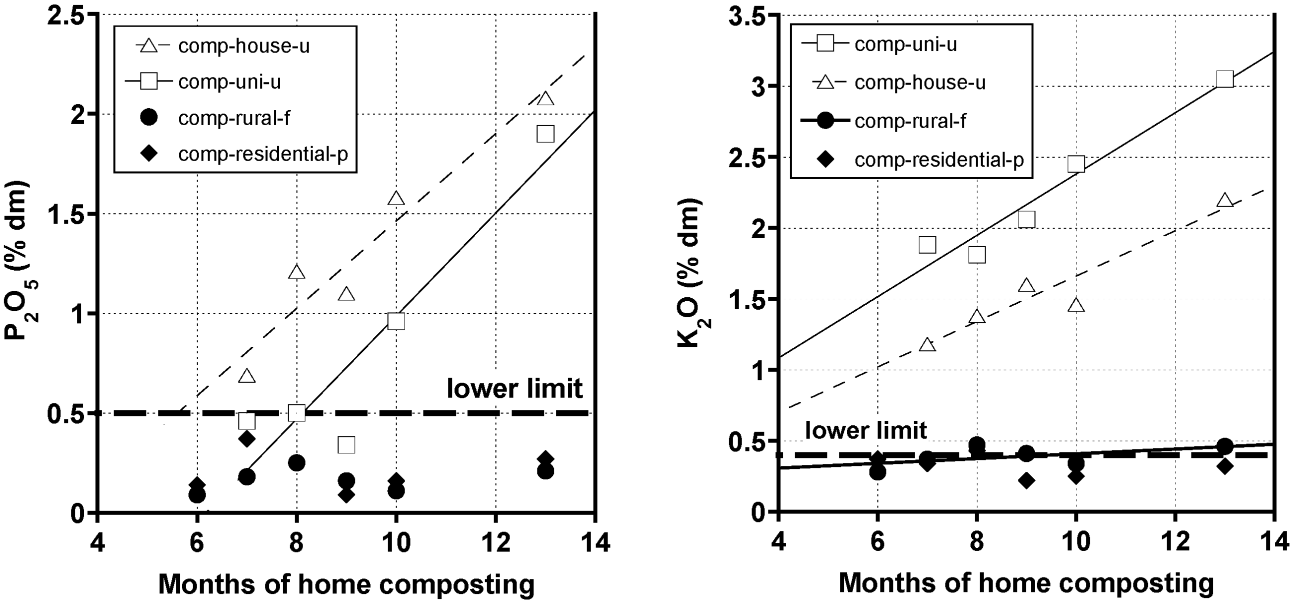

Fig. 5. Monitored experimental composters: temporal evolutions of phosphorus (as P_2O_5: left) and potassium (as K_2O: right). Symbols represent the experimental measures, and lines represent the fitted models (zero-order increase for P_2O_5 and K_2O in "comp-uni-u" and "comp-house-u" and for K_2O in "comp-rural-f"). For the adopted limits (horizontal lines), see Table 1.

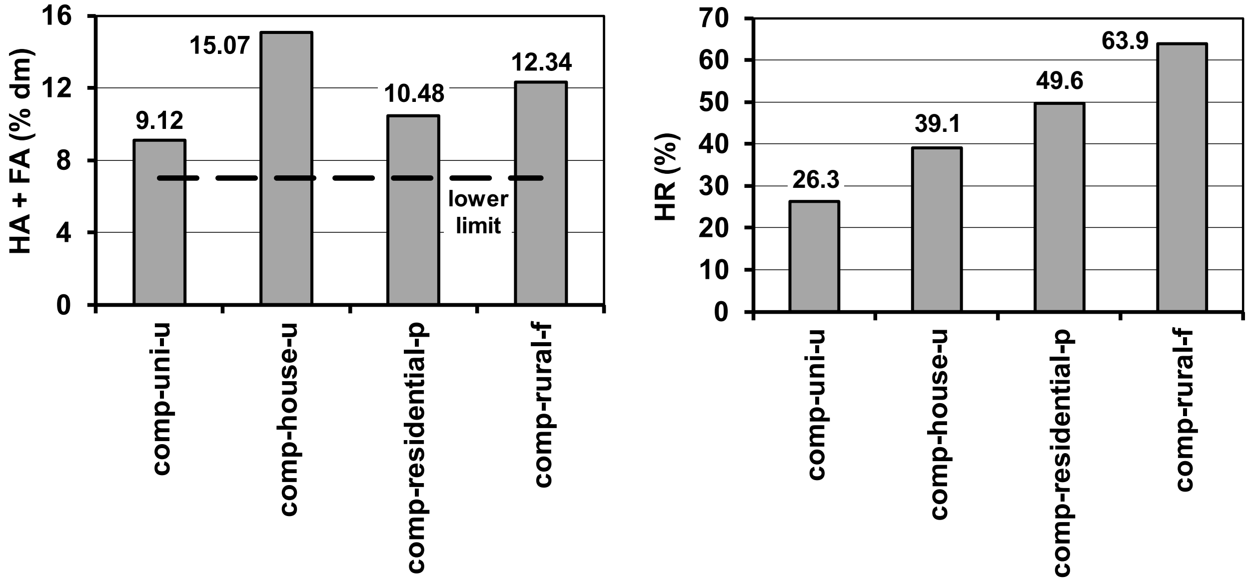

Fig. 6. Monitored experimental composters: humified organic carbon (HA + FA: left) and humification rate (HR: right) in the final (thirteenth) month of home composting. For the adopted limit (horizontal line) for HA + FA, see Table 1.

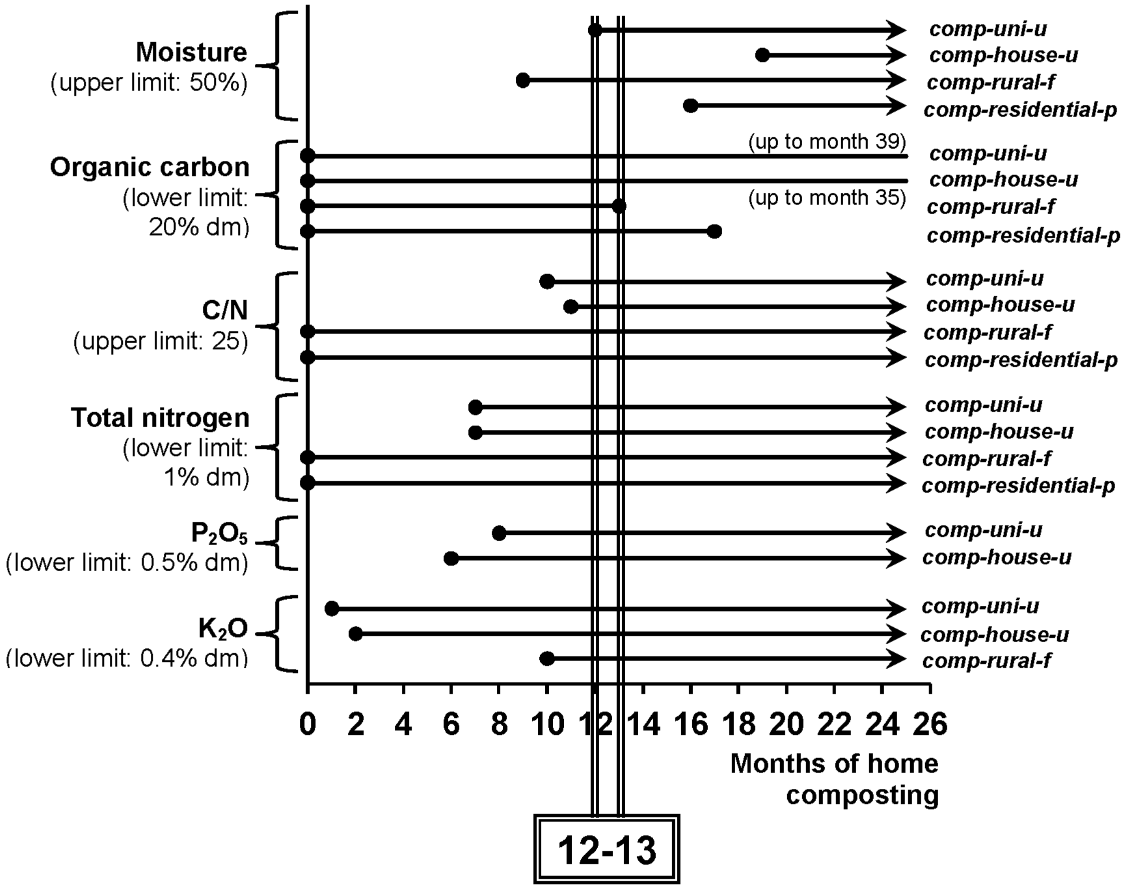

Fig. 7. Modeled parametric evolutions in the experimental composters: resulting temporal conditions of parametric compliances with the respective reference limits given in Table 1.

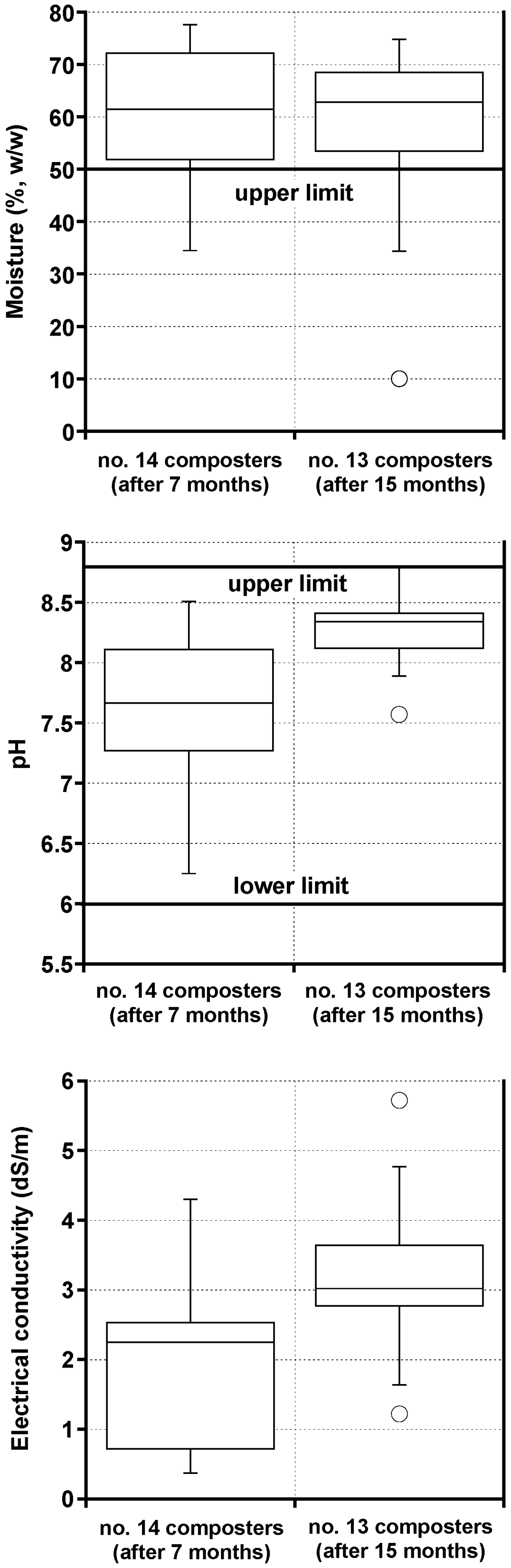

Fig. 8. Controlled provincial composters: resulting box-and-whisker plots for moisture (upper), pH (central), and electrical conductivity (lower). Legend: □ = IQR box; — = median (inside the box); vertical segments = whiskers; ○ = possible outliers. For the adopted limits (horizontal lines) for moisture and pH, see Table 1.

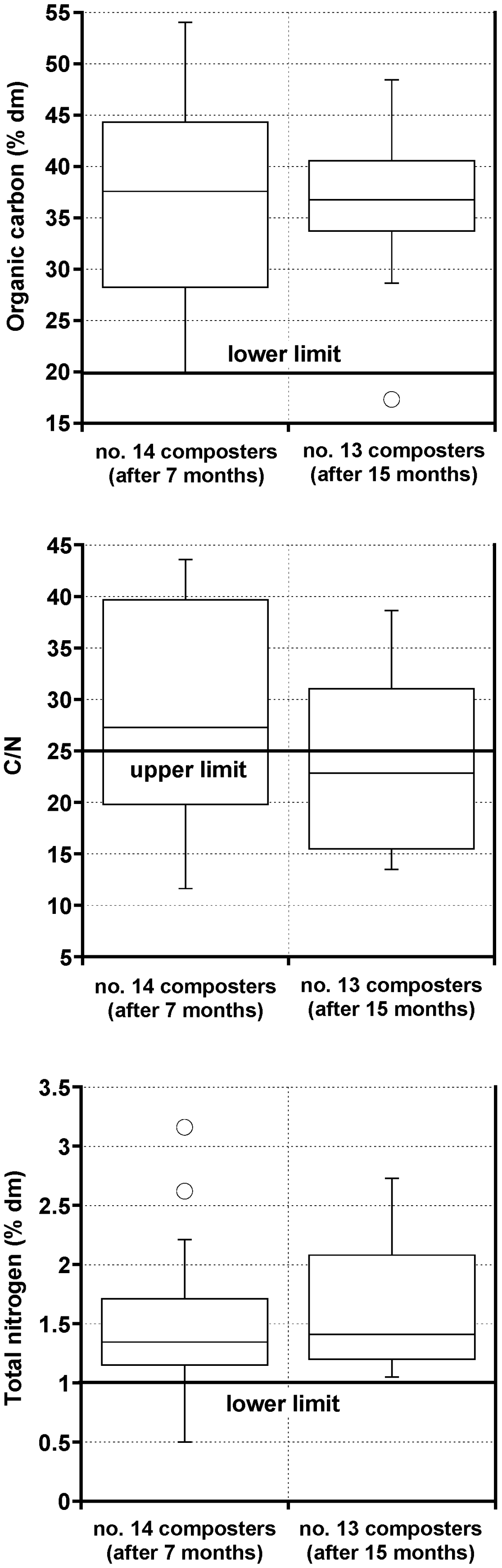

Fig. 9. Controlled provincial composters: resulting box-and-whisker plots for organic carbon (upper), C/N (central), and total nitrogen (lower). For the legend, see Fig. 8. For the adopted limits (horizontal lines), see Table 1.

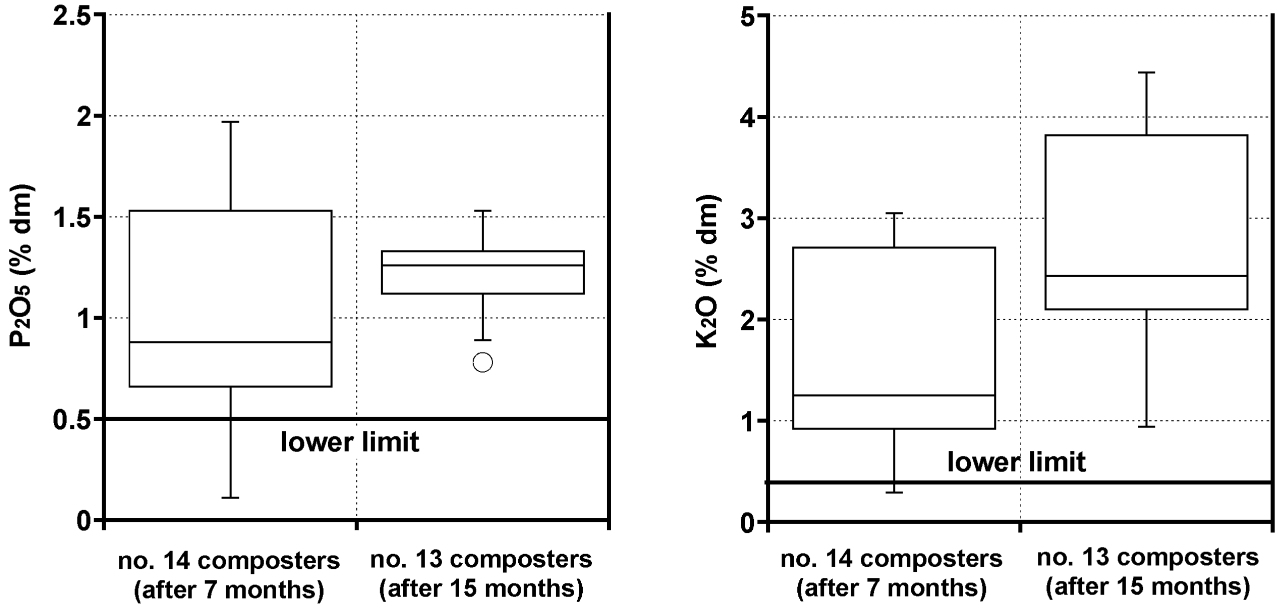

Fig. 10. Controlled provincial composters: resulting box-and-whisker plots for phosphorus (as P_2O_5: left) and potassium (as K_2O: right). For the legend, see Fig. 8. For the adopted limits (horizontal lines), see Table 1.

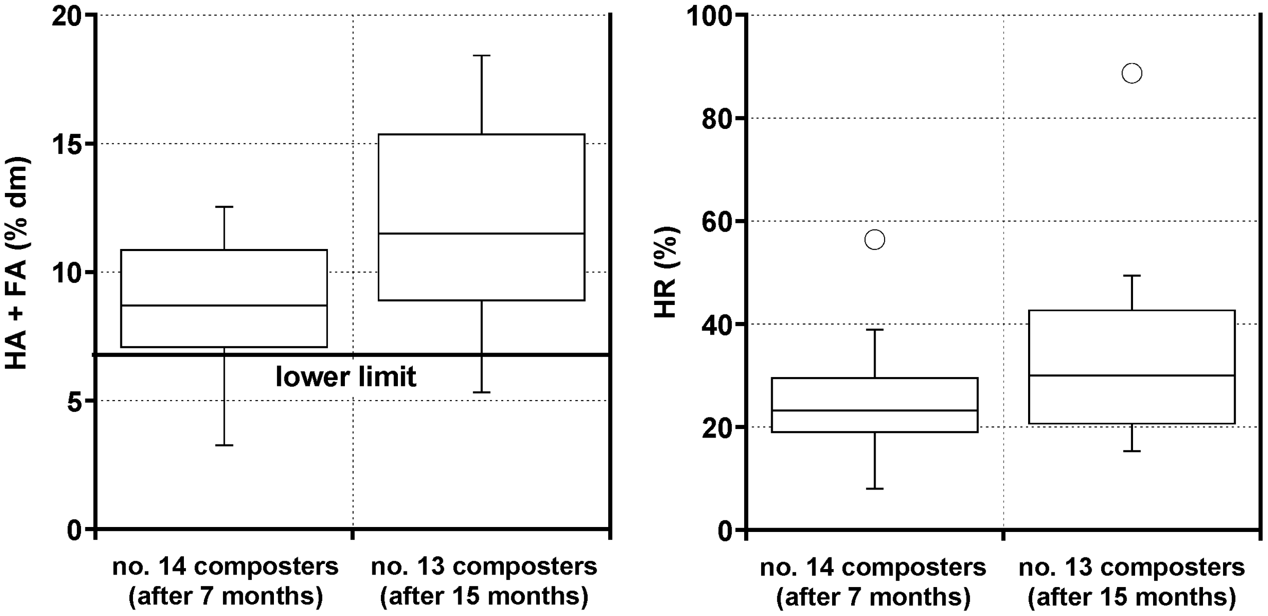

Fig. 11. Controlled provincial composters: resulting box-and-whisker plots for humified organic carbon (HA + FA: left) and humification rate (HR: right). For the legend, see Fig. 8. For the adopted limit (horizontal line) for HA + FA, see Table 1.

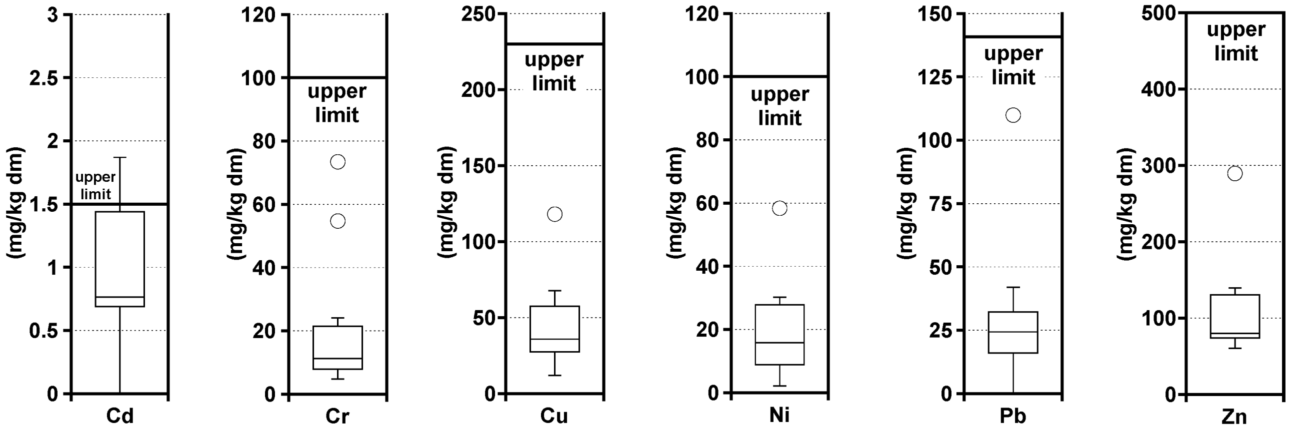

Fig. 12. Controlled provincial composters (at seven months of home composting): resulting box-and-whisker plots for heavy metals. For the legend, see Fig. 8. For the adopted limits (horizontal lines), see Table 1.