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Research Paper

Compost organic matter content varied five-fold and determined compost quality across 107 composts of the North Sea Region

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ABSTRACT

Composting is a widely used method to process organic waste residues. It results in a valuable product for soil application and use in growing media. The aim of this study was to investigate the variation in characteristics of composts produced in the North Sea Region, and the factors determining this variation. A total of 107 composts were categorized into two composting practices (produced on a farm or on a commercial composting facility) and three feedstock groups (manure combined with other wastes; green waste; fruit, vegetable and garden waste (fvg)), and measured for 67 physical, chemical and biological characteristics. Variation in the results was large, e.g., up to a factor 20 and 11 for total microbial biomass and potassium content, respectively, underlining the importance of compost characterization to target the intended compost use. Organic matter (OM) content varied between 14 and 73% of dry matter and was larger for Belgian composts compared to composts from The Netherlands, Denmark, Germany and Scotland. The OM content was positively correlated with total microbial biomass, cation exchange capacity and content of nitrogen (N) and phosphorus (P) of composts. Farm composts, irrespective of the OM effect, exhibited higher total microbial biomass compared to commercial composts. Compost prepared from green waste had lower N and P contents compared to compost prepared from fvg or manure waste. The study documents characteristics in composts from diverse composting practices and feedstocks, providing a benchmark and enabling targeted improvements as a first step towards tailormade compost.

1. Introduction

Composting is the aerobic breakdown and transformation of organic residues to a more stable end product. Both the feedstock composition and the composting conditions affect the composting process (De Corato, 2020), and therefore the end product. By adjusting the feedstock composition and process conditions, tailor-made compost products for specific applications can be targeted. However, the relationship between the processing of waste and the end product is often neglected (Liu et al., 2022) with a range of composting techniques available. When materials are composted at the farm, composting is mostly done in windrow systems (Gajalakshmi and Abbasi, 2008), which was confirmed by a survey conducted in the North Sea Region in the period 2019 to 2022 (Soilcom, 2019–2023). In these systems, the need for active aeration is low, as the relatively small dimensions of the windrow facilitate a natural chimney effect. Regular turning of the windrow is performed for additional aeration, watering, temperature control and material replacement from the boundaries of the heap towards its core and vice versa (Vandermaelen et al., 2025). Compared to composting at farms, larger volumes are composted in commercial composting facilities (De Corato, 2020; Soilcom, 2019–2023). The windrow system is less common in commercial composting facilities, and if present, limited to the

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mineralization phase. Large static piles are often used. Regular turning and watering are difficult to apply in this system possibly resulting in suboptimal oxygen and moisture conditions for composting, and excessively high temperatures (Vandermaelen et al., 2025). However, some commercial composting facilities have more sophisticated 'in-vessel' systems including forced aeration and/or enclosure of the composting material during processing allowing both the monitoring and management of the operation factors (Liu et al., 2022; Zhou et al., 2022).

Composts have been shown to have beneficial effects on soil and crops when applied to agricultural fields (De Corato, 2020; Edlinger et al., 2025), or can replace peat as a sustainable component of growing media (Bernal et al., 2017). However, compost quality can differ widely, which affects the suitability of the compost for these purposes (Chan et al., 2007; Vandecasteele et al., 2021; Vandecasteele et al., 2022). According to Bernal et al. (2009), quality criteria of compost are: contents of nutrients and organic matter, degree of maturity and hygienisation (reduction of pathogens and weed seeds) and toxicity (heavy metals, salts and xenobiotics). So far the focus has been on the conformity aspects (Cesaro et al., 2015) aiming to avoid negative effects of compost application on soil or crop. There is a lack of knowledge on variability of key compost characteristics across geographical locations, producers, and feedstocks in the positive aspects of compost quality.

An important compost quality characteristic is the organic matter (OM) content. Composts with higher OM content are more suitable as peat replacement in growing media (Vandecasteele et al., 2021). When added to soil, composts have been shown to improve chemical, biological and physical soil characteristics especially by the increase in soil OM content (Bernal et al., 2017; De Corato, 2020; Hefner et al., 2024). Large OM contents can be found in unstable composts (Kupper and Fuchs, 2007) and therefore, OM content should be evaluated in relation to compost stability (related to microbial transformation of organic matter) or maturity (suitability for plant production). There is a lack of knowledge of how feedstock and composting practice affect the OM content and quality of the end product.

The cation exchange capacity (CEC), microbial biomass content and nutrient composition can also serve as key quality parameters for compost. The CEC increases during the composting process (Harada and Inoko, 1980; Smith and Hughes, 2004), enhancing the material's ability to retain nutrients. This improvement can contribute to greater soil fertility, reducing the need for frequent fertilizer additions. High microbial biomass, including bacteria, fungi, and actinomycetes, benefits soil health (Joos, 2023). Compost application to soil can induce a priming effect on the soil microbiome, but also inoculate the compost microbiome into the soil (Luo et al., 2022). Microbial composition is commonly investigated using DNA-based methods; however, phospholipid fatty acid (PLFA) analysis is also employed to assess variations in microbial abundance (Siles et al., 2024; Vandecasteele et al., 2021). DNA-based techniques offer valuable insights into microbial community functionality, though their results are inherently expressed on a relative base. In contrast, PLFA is able to assess absolute values of microbial biomass groups (Laine et al., 2025; Siles et al., 2024), also in compost (Vandecasteele et al., 2021). Microbial biomass content can vary between compost end-products (Pot et al., 2022), but it is not clear what the underlying or determining factors are. The nutrient composition of compost is another important aspect for the targeted use of composts in soil and growing media. Depending upon the specific needs of soil, plant and ecosystem, high or sometimes low amounts of N, P, K and other nutrients are favorable.

In most studies, compost characterization is limited to a small number of composts, sometimes measured at several stages of the composting process. Literature search revealed only a few studies with an overview of compost characteristics values on a larger scale and not limited to a few composting facilities (Bernal et al., 2017; Faverial et al., 2016; Kupper and Fuchs, 2007; Montejo et al., 2015). Two of these studies had the disadvantage that compost characterization was performed by multiple laboratories with possibly diverging measuring protocols, potentially influencing results (Bernal et al., 2017; Faverial et al., 2016). For the North Sea Region, benchmark information is lacking on the mean and variability of compost end product characteristics, originating from a range of different composting practices, facilities and feedstock compositions. Composting in the North Sea Region is characterized by a strong tradition of source-separated biowaste collection, especially in Flanders, the Netherlands, and Germany. These regions combine this with professional treatment systems and, especially in Belgium, strict quality assurance (Vlaamse Regering, 2019), leading to high-quality compost production. Composting methods in the North Sea Region vary from open windrows to enclosed systems, with farm-scale composting practiced across the region, often intensively but on a smaller scale. Unravelling mechanisms behind compost quality will enable steering towards high quality or tailor made compost production, and can facilitate fast screening of compost quality. To understand variability further, data on 107 diverse composts from the North Sea Region were compiled. Sixty-seven physical, chemical and biological characteristics were measured on the composts, by one single laboratory per characteristic. We wanted to quantify the variability in compost quality parameters among composts originating from different composting practices and feedstock types, and to identify and statistically evaluate the main factors influencing compost quality. It was hypothesized that composting practices and feedstock affect chemical and biological characteristics of the final compost product, thereby providing guidance for the production of tailor-made composts for specific end uses.

2. Materials and methods

2.1. Compost origin

Compost characteristics were measured for a set of 119 composts from both commercial and farm composting facilities in the North Sea region (Europe), derived from a range of feedstocks. Four sets of composts were used. The first set of 64 composts was sampled in the framework of the Interreg North Sea Region project Soilcom (2019–2023) covering Flanders (Belgium), The Netherlands, Scotland, Germany and Denmark. The aim was to assess compost quality in the North Sea region and observe variations across different types of feedstock, composting methods (farm and commercial composting) and time (2019–2022). Composts from the same compost producer were sampled in different years and/or were produced from different feedstocks. For the second, third and fourth compost set, data collected from previous studies were used. The second set of 30 composts was sampled during 2019–2020 at Belgian commercial composting companies as part of the Bi-o-ptimal@work project regarding sustainable cultivation by innovative and local materials (Pot et al., 2022; Vandecasteele et al., 2021). A third set of 23 composts was sampled in 2013 and 2014 from 9 Belgian commercial composting companies as part of the Syneco experiment regarding removal of woody biomass before composting (Vandecasteele et al., 2016). Only the control composts from the standard composting practice were selected. A fourth set of 8 composts was collected in 2013 and 2014 from 4 Belgian farm composting facilities (Viaene, 2016). One facility provided four, another facility two composts and two facilities just one compost, all from different feedstocks. For the analysis in the current study, 12 composts were left out from data analysis, resulting in a decreased dataset of 107 composts. Five of these composts came from small scale static composting experiments according to the Johnson-Su method (Johnson and DeSimio, 2017). Seven of these composts came from one commercial compost producer with composting practices (windrows) and feedstocks (manure and peat) diverging from common commercial compost producers. A map with an overview of the origin of the 107 composts can be found in the supporting information (Fig. S1).

2.2. Compost sampling

A compost sample was composed by taking 10–20 (depending on the batch volume) spatially distributed subsamples from the heap. For the third compost set, two samples were taken from every heap and the average of the results of the duplicate analysis was used. For the fourth compost set, the average was taken from three samples originating from 3 replicate piles.

2.3. Compost characteristics

2.3.1. General information

For each compost sample, the country of origin, year of sampling, and producer was noted. 'Farm' or 'Com' were assigned for the 'Composting practice' variable to define whether the compost was produced on a farm (Farm) or by a commercial composting facility (Com). Using information on feedstock obtained from the producer the composts were segregated by variables 'Feedstock' and 'Feedstock group' derived from one of the seven or three possible categories respectively (Table 1).

In addition to general information, 67 physical (five basic parameters, two on impurities, eight on sieving), chemical (two basic parameters, five on organic composition, three on stability, 21 on nutrient content and six on CEC) and biological compost characteristics (one on contamination, seven on PLFA and seven on nematodes) were measured (details below). All chemical, biological and part of the physical characteristics were analysed at ILVO (Belgium). Only the particle size distribution was analysed by James Hutton Institute (UK, Scotland). Methodological details of characteristics relevant for underlying study are given below, while other measurements details are described in the supplementary information. Fresh material was stored at 4 °C before analysis. Analyses on fresh materials were started within two weeks after sampling. Some analyses were performed on dried material. The material was dried for 24 h at 70 °C, mechanically ground in a cross beater mill (SK100, Retsch, Haan, Germany) equipped with heavy-metal-free grinding tools and internal 1 mm sieve with samples stored post processing in polypropylene containers prior to analysis. The material dried at 70 °C was further dried at 105 °C for four hours to assess the residual moisture content in order to recalculate results, assessed on material dried at 70 °C, in units on dry matter (dried at 105 °C).

All raw results of the compost characteristics are available at Zenodo (Amery et al., in press).

2.3.2. Physical characteristics

Laboratory compacted bulk density was determined on the fresh material (EN 13040). Moisture and dry matter content were assessed by drying the material at 105 °C (EN 13040). The assessment of stones (>5 mm) and impurities (>2 mm) was started from fresh material (CEN/TS 16202). Determination of the particle size distribution is described in the supplementary information.

Table 1
Feedstock categories and Feedstock groups.

Feedstock group	Feedstock	Description	Number of composts in the dataset
Green	Green	Main feedstock from garden or park residues, biodegradable waste that can be composed of plant material such as grass or flower cuttings, hedge trimmings and brush	64
	Wood	Wood as most significant component of the feedstock	2
	Peat	Peat and/or growing media as one of the feedstocks	2
	Farm-plant	Farm composts without farm yard manure	11
Manure	Manure	Composts with farm yard manure as one of the feedstocks	16
Fvg	Fvg	Feedstock of fruit, vegetable and garden waste	5
	Digestate	Digestate as one of the feedstocks	7

2.3.3. Chemical characteristics

The electrical conductivity (EC, EN 13038), pH-H_2O (EN 13037) and NO_3^--N and NH_4^+-N concentrations were measured in a 1:5 (v:v) solid-water extract of fresh compost. NO_3^--N concentrations were measured in the extract with a Dionex DX-3000 IC ion chromatograph (Dionex, Sunnyvale, CA), NH_4^+-N concentrations with a Skalar SAN++ flow analyser (Skalar Analytical B.V., Breda, The Netherlands).

Determination of OM content was done according to EN 13039 by ashing the dried and ground compost in a Heraeus muffle oven at 450 °C. The stability of the fresh compost sample was assessed by a closed respirometer (EN 16087–1). The oxygen uptake rate (OUR, expressed as mmol O_2/kg OM/hour) was measured as the microbial activity in the closed Oxitop respirometer of the compost mixed with buffered mineral medium at 20 °C based on EN 16087–1 and the method reported by Grigatti et al. (2011).

The biodegradation potential (Vandecasteele et al., 2017) was calculated as the holocellulose/lignin ratio, based on the biochemical analysis with an Ankom 220 Fiber Analyser extraction unit according to van Soest et al. (1991).

Total carbon (TC) and total nitrogen (TN) content of the dried and ground compost were measured by dry combustion at 1100 °C using a Skalar C/N-Analyser Primacs SNC100-IC. The inorganic carbon (IC) content was measured after acid addition. The organic carbon (OC) content is the result of TC minus the IC content of the sample (NBN EN 15936). The C/N ratio is the ratio of the organic C (OC) content over the total nitrogen (TN) content (mass based). Total elemental contents of phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), manganese (Mn) and arsenic (As) were measured by a 5110 VDV Agilent ICP-OES (Agilent, Santa Clara, CA, USA) after digestion of the dried and ground material with 4 mL HNO_3 (p.a. 65 %) and 12 mL HCl (p.a. 37 %) in an SCP Digiprep MS 200 heating block.

The cation exchange capacity (CEC) was determined by ammonium acetate at pH 7.0 and KCl, modified from the method by Rajkovich et al. (2012) as described by Viaene et al. (2023).

2.3.4. Biological characteristics

To assess the number of germinating weed seeds in the material, 500 ml of the fresh compost was mixed with 2 L of peat, moistened and placed on a spot with sufficient daylight. The number of weeds seeds emerging after 14 days was counted.

PLFAs were extracted from the compost samples by a method modified from Bligh & Dyer (1959) as described in Pot et al. (2022). The percentage of fungi biomass in the total biomass (%Fungi) was calculated by dividing the fungi biomass by the sum of biomasses from non-specific, Gram+, Gram- bacteria and fungi (expressed as percentage). Nematode analysis and the derived indices are described in the supplementary information.

2.4. Statistical analysis

Data were analysed using generalized linear mixed models (Pinheiro and Bates, 2004) to account for the hierarchical structure of the dataset, with composts grouped by producer and measured across years. A generic model was specified as:

$$\text{Response} \sim \text{Covariates} + \text{Origin} + (1 \mid \text{Producer:Year})$$

Because the response variables were strictly positive and exhibited heteroscedasticity (as revealed by exploratory data analysis), the gamma distribution with a log link was chosen (McCullagh and Nelder, 1989). Origin was included as a fixed effect with three levels: (i) Belgian composts from set 1, (ii) Belgian composts from sets 2, 3, and 4, and (iii) composts from The Netherlands, Scotland, Denmark, and Germany. Producer was treated as a random effect, and to allow for repeated measurements for producer, year was modelled as a random factor nested within producer.

The influence of feedstock group and composting practice on compost characteristics was evaluated using linear regression models with feedstock and practice as categorical predictors. In addition, regression models with OUR, total microbial biomass, CEC, total N and total P as response variables were constructed, including the log of OM content as a continuous covariate in interaction with feedstock group or composting practice. Preliminary analysis with OM in the original scale resulted in unrealistic models, so the log-model was preferred. When multiple biologically plausible models were available, model selection was based on the Bayesian Information Criterion (BIC). This criterion was preferred over the Akaike Information Criterion (AIC) because, with data originating from different sources, complex models may capture imbalances in the data rather than true effects. Final candidate models were subjected to regression diagnostics (Kutner et al., 2005), including assessment of residual distributions, and evaluation of heteroscedasticity.

Statistical analysis was performed using R version 4.5.0 (R Core Team, 2013; The R Foundation for Statistical Computing, 2025) in conjunction with RStudio (version 2025.05.0). Model fitting was done with the glmer function from lme4 (Bates et al., 2015) with family = Gamma and the log as link function. Visualization of the regression models was done by ggpredict (Lüdecke, 2018), and comparison between the group means by emmeans (with multiple comparison with Tukey correction) from the emmeans package (Lenth et al., 2023). Values below the limit of quantification (LOQ) were replaced by half of the LOQ. Relations and differences were categorized as statistically significant if the *P* value was below 0.05.

3. Results

3.1. Variation in full dataset results of measured characteristics

Compost characteristics varied widely over the 107 composts. A general overview is given in Table 2, and histograms are available in the supplementary information (Fig. S2). Not all of the 67 characteristics are shown, the raw data of the complete dataset is available on Zenodo (Amery et al., in press). All 107 composts had measured values of DM and OM content, pH, TN, total P, total K and EC. The mean OM content was 36 % of DM, and 19 % on moist (fresh) mass compost. Almost all composts (93 %) had pH values between 7 and 9. There was a broad range of CEC values, from 17 to 68 $\text{cmol}_c\ \text{kg}^{-1}$. Both TN content and C/N ratio varied 4- to 5-fold, whereas total P and total K content varied by a factor 7 and 11, respectively. In almost all composts, heavy metal concentrations and impurity contamination were below the maximum values imposed by the European Quality Assurance Scheme of the European Compost Network (ECN-QAS) (Siebert and Gilbert, 2018) and by the EU Fertilising Product Regulation (Regulation (EU), 2019) for PFC1A (organic fertilisers) and PFC3A (organic soil improvers). Exceptions were three composts with > 4 % stones. In almost half of the farm composts with weed seed analysis, germinating weed seed were found (9 out of 19 farm composts, 2 – 54 per liter). In contrast in only 2 of 25 commercial composts with weed seed analysis, a small amount of germinating weed seeds were detected (2 per liter).

The EC varied from very low salt content (13 mS m^{-1}) to very salty (373 mS m^{-1}), which is above the threshold for use in substrates of 190 mS m^{-1} by ECN-QAS. The EC of the green composts (mean 76 mS m^{-1}) was statistically smaller compared to the EC of the manure (mean 149 mS m^{-1}) and fvg composts (mean 139 mS m^{-1}).

A large part of the 97 composts for which stability was measured by OUR could be categorized as 'very stable' (53 composts with OUR < 5 $\text{mmol O}_2\ (\text{kg OM})^{-1}\text{h}^{-1}$) or 'stable' (29 composts with OUR between 5 and 10 $\text{mmol O}_2\ (\text{kg OM})^{-1}\ \text{h}^{-1}$), according to the compendium for analyses in the environmental legislation in Flanders, Belgium (Vlaamse Regering, 2019). The OUR showed not to be different between feedstock groups nor farming practice. However, the biodegradation potential proved to be larger for farm than for commercial composts.

3.2. Organic matter content

The OM content of DM in the 107 composts varied widely between 14 % and 73 %, with a median of 34 %. The OM content was best explained by the origin group (statistical details in the supplementary information). Composts from Belgium showed higher OM contents (mean of 41 % and 37 % of DM, from compost set 1 and from the other sets, respectively) than composts from The Netherlands, Denmark, Germany and Scotland (mean of 23 % of DM) (Fig. 1). Composts from the green feedstock group had slightly lower OM values compared to the composts from fvg and manure, but this effect was not significant. Largest OM values were observed for farm composts, but the OM content of farm composts was in general not significantly larger than for commercial composts (Fig. 1). The OM content was not related to the stability of the compost measured as the biodegradation potential (*P* = 0.06). There was a significant but small effect of the OM content on the stability quantified as the OUR (*P* = 0.005), with a large remaining variability (Fig. 2, statistical details in the supplementary information).

Table 2
Overview of characteristics of the 107 composts: DM (dry matter) content, OM (organic matter) content, total microbial biomass, pH, CEC (cation exchange capacity), total N, total P, total K, OUR (oxygen uptake rate), EC (electrical conductivity), C/N (C over N ratio).

Variable	Unit	N[a]	Mean	St. dev.[b]	Min[c]	Pctl.[d] 25	Median	Pctl. 75	Max[e]
DM	% of fresh material	107	56	13	23	50	58	65	84
OM	% of dry matter	107	36	12	14	28	34	42	73
Total biomass	nmol g^{-1}	55	392	329	76	167	294	528	1514
pH	–	107	8.3	0.6	5.8	7.9	8.4	8.7	9.2
CEC	$\text{cmol}_c\ \text{kg}^{-1}$	40	42	13	17	33	41	51	68
Total N	% of DM	107	1.5	0.54	0.58	1.0	1.4	1.8	2.8
Total P	g (kg DM)^{-1}	107	2.4	1.1	0.9	1.7	2.1	2.8	6.8
Total K	g (kg DM)^{-1}	107	10	6.4	2.9	5.4	8.9	11	31
OUR	$\text{mmol O}_2\ (\text{kg OM})^{-1}\ \text{h}^{-1}$	97	5.8	4.3	< 0.8	2.7	4.4	7.6	25
EC	mS m^{-1}	107	109	66	13	63	94	133	373
C/N	g g^{-1}	63	14	3.5	8.7	12	14	16	29

[a] N: number of composts analysed.

[b] St. dev.: standard deviation

[c] Min: minimum value.

[d] pctl.: percentile.

[e] Max: maximum value.

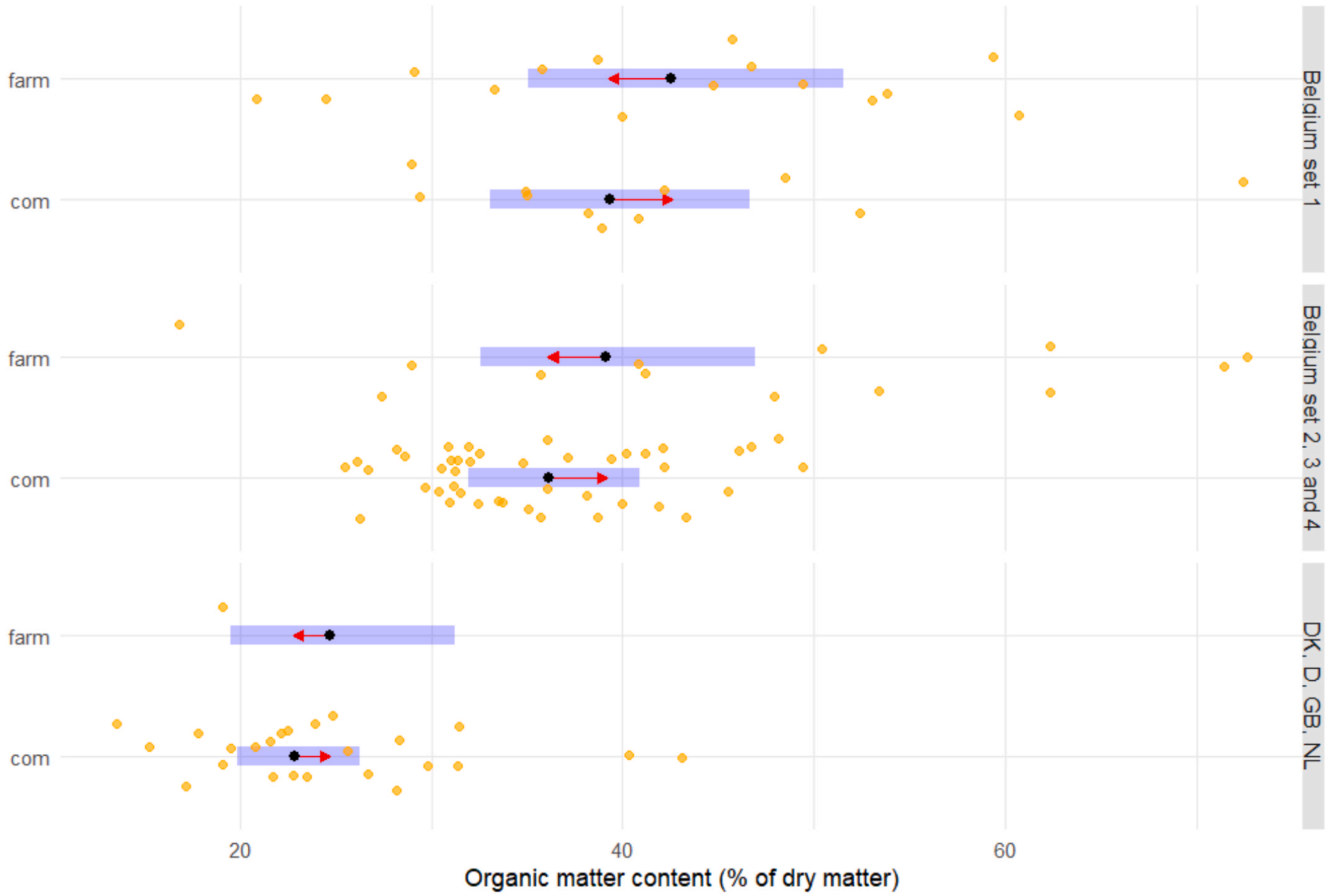

Fig. 1. The organic matter content (% of dry matter) of composts explained by the origin group (from top to bottom: Belgian composts from set 1; Belgian composts from set 2, 3 and 4; composts from The Netherlands, Denmark, Germany and Scotland) and composting practice (farm: farm composting; com: commercial facility composting). The blue bars give the confidence intervals around the expected means. The red arrows are a summary of the post-hoc comparisons. If the red arrows do not overlap, the means are significantly different. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

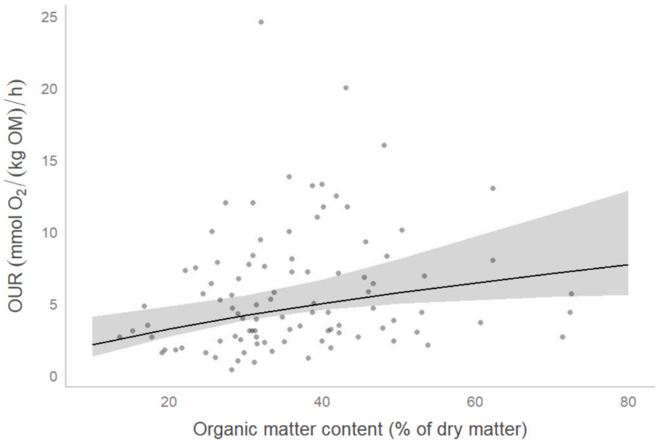

Fig. 2. The oxygen uptake rate (OUR) of composts explained by organic matter content. Measured values are given as points, the model prediction as a line with 95% confidence interval.

3.3. Total microbial biomass

Total microbial biomass in 55 composts measured by PLFA analysis varied 20-fold between 76 and 1514 nmol (g dry matter)$^{-1}$. Gram positive and nonspecific bacteria biomass represented together more than half of the total microbial biomass based on mean values, and mycorrhiza and total fungi each less than 10 % of the total microbial biomass. Biomass of the different functional groups varied similarly and was correlated to all other groups and the total biomass (Fig. S3), with Pearson correlation coefficients varying between 0.31 and 0.98. Given these correlations, further analysis focused on the total microbial biomass only.

Total microbial biomass in composts was explained by OUR ($P < 0.001$) with less stable composts (high OUR) showing larger biomass contents. However, total biomass was much better explained by the OM content of compost and the composting practice (Model biomass, Fig. 3, statistical details provided in the supplementary information). At low OM contents, there was little difference in total microbial biomass of farm versus commercial composts. Total microbial biomass increased with OM content, but this increase was larger for farm composts than for commercial composts. The proportion of fungi ranged from 0.1 % to 26 % of total microbial biomass (fungi and bacteria), but was not explained by OM content, feedstock group nor composting practice (details not given).

3.4. Cation exchange capacity

The CEC of the composts varied 4-fold between 17 and 68 cmol$_c$ (kg)$^{-1}$. Since the number of measured CEC values was unbalanced between the feedstock groups, this variable was not considered in the model for CEC. The CEC was best explained by the OM content and not

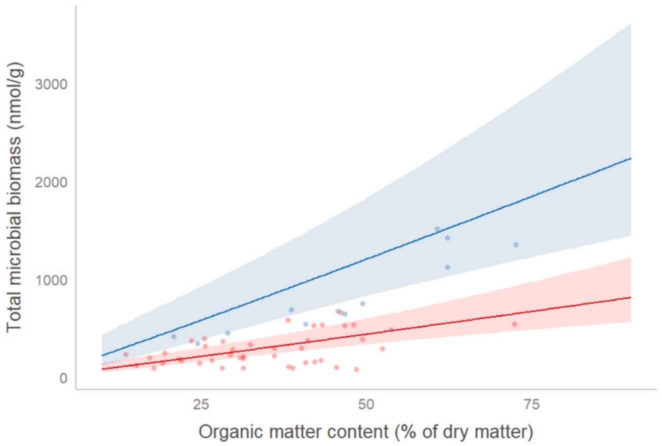

Fig. 3. The total microbial biomass of composts explained by organic matter content and composting practice (blue: farm composts, red: commercial composts). Measured values are given as points, the model prediction as a line with 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by the composting practice (Model CEC, Fig. 4, statistical details provided in the supplementary information). The CEC was not related to the OUR of the composts.

When ignoring the possible role of mineral parts in the CEC, the ratio of CEC over OM content (CEC/OM) gives an estimate of the negative charge per unit of OM. The CEC/OM was explained by the compost OUR (model CEC/OM, Fig. 5, statistical details provided in the supplementary information), and not by the composting practice. A very similar model explained CEC/OM by the NO_3^- over NH_4^+ ratio (positive correlation).

3.5. Nutrient contents in compost

The nutrient status of composts varied widely. For example, the total N content ranged almost 5-fold from 0.58 % to 2.78 %. For other nutrients, the range was even larger: 7-fold for total P, 11-fold for total K (Table 2) and 8-fold for total Mg content (1.0 to 9.6 g kg^{-1}). Total contents of different nutrients were all positively correlated (pairs and correlation plots in Fig. S4). In particular, total N, P, K and Na contents were strongly correlated, as well as total Mg and Ca contents. Heavy metal contents (pairs and correlation plots in Fig. S5) had much lower correlation coefficients, with the exception of Cr and Ni, and Cu, Pb and Zn (all positively correlated).

The C/N ratio ranged between 8.7 and 29, and was significantly different between feedstock groups, with smallest mean C/N values for manure and largest values for green composts.

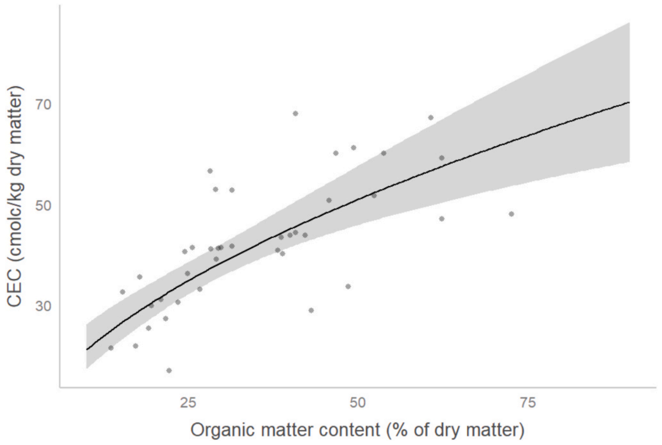

Fig. 4. The cation exchange capacity (CEC) of composts explained by organic matter content. Measured values are given as points, the model prediction as a line with 95% confidence interval.

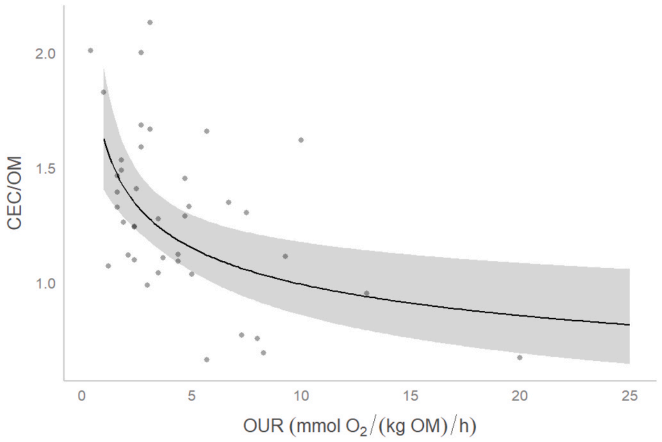

Fig. 5. The ratio of CEC over organic matter content explained by the oxygen uptake rate (OUR, estimate of stability) of composts. Measured values are given as points, the model prediction as a line with 95% confidence intervals.

Similarly to total microbial biomass and CEC, total N contents were positively related to OM contents (Model N, see statistical details in supplementary information, Fig. 6). In contrast to total microbial biomass, the total N content was better explained by feedstock group than by composting practice. At the mean OM value of 36 % of DM, composts of the green feedstock group had significantly lower total N contents (1.30 %) compared to composts of manure (1.59 %) or fvg feedstock groups (1.76 %).

A very similar model with OM and feedstock group best explained total P values in composts (Model P, see supplementary information for details, Fig. 6). As for total N, at the mean OM content of 36 %, total P values were lower for composts in the green feedstock group (1.93 g (kg DM)$^{-1}$) compared to the total P for manure (3.11 g (kg DM)$^{-1}$) and fvg composts (3.26 g (kg DM)$^{-1}$).

4. Discussion

4.1. Variation in compost characteristics

This comprehensive assessment of compost was assessed across a diverse collection of samples. Compost characteristics were observed to vary from three- to thirtyfold, highlighting the limits of using fixed 'average' values and emphasizing the need for individual compost assessment. Importantly, this work shows variability in a product that could easily be defined as just 'compost'. This study investigated diverse composts with a wide range in origin, feedstock and composting practice. This compilation of compost characteristics and their variations brings new knowledge with few studies to date found in literature, e.g. the compilation of published characteristics from 442 composts of temperate and tropical origin (Faverial et al., 2016), a French report on 86 Swiss composts (Kupper and Fuchs, 2007), a study on 30 composts from 10 Spanish sites (Montejo et al., 2015) and a compilation of different studies by Bernal et al. (2017). The pH values reported in the present study (Table 2 and Fig. S2) were comparable to or higher than those found in the four referenced studies, whereas the levels of TOC, TN, and OM (Table 2 and Fig. S2) fell within the lower range of values reported by those studies. Compost total K values were similar (Faverial et al., 2016) or slightly higher (Kupper and Fuchs, 2007; Montejo et al., 2015) than in the present study. Compared to our study, composts in other studies had lower (Bernal et al., 2017), slightly higher (Kupper and Fuchs, 2007; Montejo et al., 2015) or much higher (Faverial et al., 2016) total P contents. The mean C/N ratio of the current study was in between the mean values of Montejo et al. (2015) and Faverial et al. (2016).

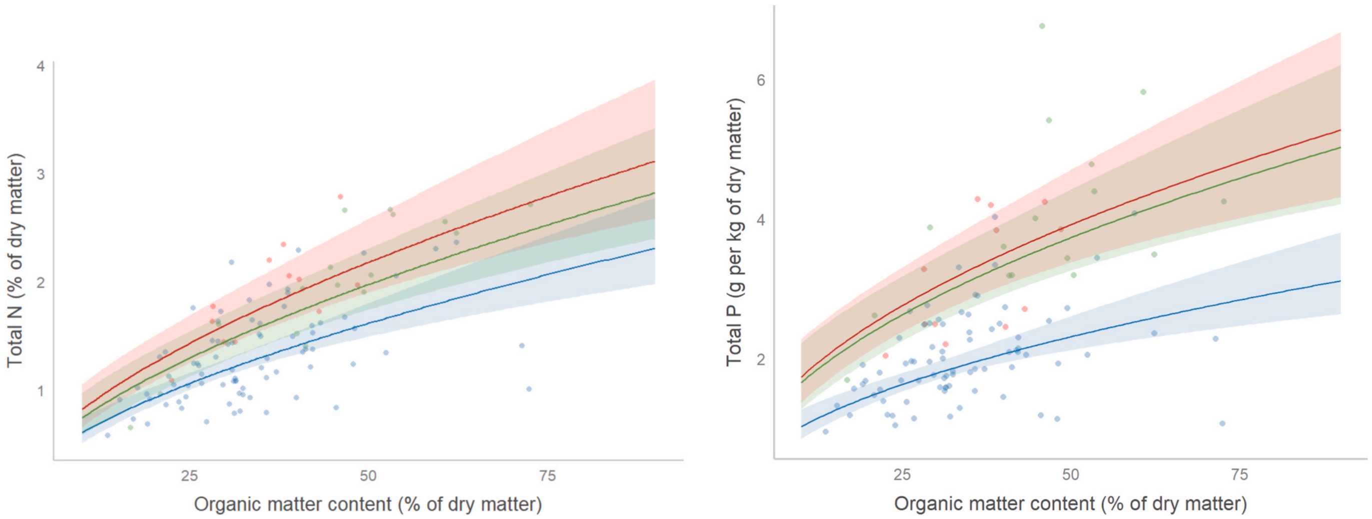

Fig. 6. The total N content (left) and total P content (right) of composts explained by the organic matter content and the feedstock group (manure: green; green waste: blue; food vegetable and garden waste: red). Measured values are given as points, the model prediction as a full line with 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Compost densities in the current study were slightly (Kupper and Fuchs, 2007) to much lower than the densities of the Spanish composts (Montejo et al., 2015).

The EC varied almost 30-fold. Compared to the study of the 86 Swiss composts (Kupper and Fuchs, 2007), a much larger and significant difference in EC of fvg feedstock group composts compared to green feedstock group composts was observed. Most of the nutrients in the fvg feedstock are retained in the compost throughout the composting process, which leads to composts with a comparatively high salt content.

For all composts, heavy metal contents were below the maximum values of the European Quality Assurance Scheme of the European Compost Network (ECN-QAS) (Siebert and Gilbert, 2018) and of the EU Fertilising Product Regulation (Regulation (EU) 2019/1009) for PFC1A (organic fertilisers) and PFC3A (organic soil improvers). Except for Cd, in general lower heavy metal contents were observed compared to the Swiss (Kupper and Fuchs, 2007) and Spanish composts (Montejo et al., 2015). Also the content of macroscopic impurities was for all composts of the current study below the legal maximum limit of CMC3 in the EU Fertilising Product Regulation (Regulation (EU) 2019/1009), in contrast to the high contamination in 30 Spanish composts (Montejo et al., 2015). Relatively more farm than commercial composts contained viable weed seeds. This can possibly be attributed to insufficiently high temperatures during the farm composting process (Grundy et al., 1998). Three days at 55 °C is sufficient to destroy weed seeds. Due to insufficient turning during the breakdown phase, these temperatures might not be reached in the windrow or part of it. Farm composts are also at higher risk to be contaminated with weed seeds during the maturation phase, where temperatures are typically lower given the pile dimensions and where the presence of weed seeds in the farm environment is higher compared to commercial composting sites.

Compost quality is frequently evaluated in terms of its limitations, such as immaturity and contamination; however, this study emphasizes its beneficial characteristics. Values presented in this study offer the opportunity in the future to benchmark compost characteristics from other or new composts, also on these positive aspects. This can help selecting compost for specific applications. This paper focused on the largest part of the measured (bio)chemical measurements, while also data on extra physical and chemical measurements and nematode determination are available for the same dataset (Amery et al., in press).

4.2. *Organic matter content*

The OM content of the compost dry matter varied 5-fold and was not related to the composting practice nor compost feedstock. The origin of the compost was identified as the principal explanatory variable, with composts from Belgium having significantly larger OM values than the composts from The Netherlands, Scotland, Denmark and Germany. The primary explanation for this observation is the stringent regulatory framework in Flanders, the northern region of Belgium where all Belgian composts from this study were produced. In most countries there are only voluntary quality criteria for compost, with still possibilities for the producers to use or sell the compost as waste material when these quality criteria are not met. In contrast, in Flanders all compost producers are certified and controlled regarding the legislative criteria (Vlaamse Regering, 2019). Moreover, the quality criteria for OM content are rather low in The Netherlands (10 % OM of DM (BVOR, 2023)), Germany (15 % OM of DM (BGK, 2023)) and the European Quality Assurance Scheme (15 % of DM (Siebert and Gilbert, 2018)). All of the 107 composts in the dataset comply to the Dutch criterium, and only one compost has an OM content below 15 % of DM. The criterium for OM content in Flanders is 16 % (Vlaamse Regering, 2019), but this is expressed on fresh matter and not on dry matter. With a mean DM content of 56.4 % this corresponds to a mean criterium of 28.4 % OM on DM. From the 107 composts, 37 composts have a OM content below 16 % DM on fresh matter. Belgian compost producers are encouraged to monitor the feedstock materials in order to reach a sufficiently high OM content in the end product. Compost producers need to be critical on the level of soil contamination of the feedstock, and ensure an adequate share of brown or woody material in the feedstock.

The OM content generally decreases during composting with higher OM contents indicating an incomplete composting process (Bernal et al., 2017). For the dataset in this study, there was no relationship between the OM content and the biodegradation potential. There was a significant but small effect of OM content on the OUR, but the large variability (Fig. 2) suggests that over a range of diverse composts as end products, OM content is not a good measure of the compost stability.

4.3. *Microbial biomass*

There was a very large variation (20-fold) observed in the compost microbial biomass. Larger total microbial biomass was observed for less stable composts (larger OUR). This is to be expected since the oxygen consumption in the unstable composts is related to microbial activity and therefore to microbial biomass. However, the model screening showed that the variation in total microbial biomass was better explained by the OM content. The tight relationship of microbial biomass and OM is explained by the fact that heterotrophic organisms feed on organic matter. The presence of organic matter is a condition for microbial abundance and organic matter is a key source of carbon in soils (Hu et al., 2014; Patra et al., 2008). Additionally, the composting practice affected the compost total microbial biomass content. At equal OM content, microbial biomass was larger for farm compared to commercial composts. This difference is more pronounced at larger OM contents. A possible explanation for this observation could be differences in type or quality of organic matter in farm versus commercial compost related to colonization and growth of the microbial population. Feedstock can have an effect here, with e.g. OM derived from manure being more attractive to microbial colonization compared to green waste OM. Another explanation could be the surrounding conditions of the composting facilities. The farm environment, soil, crop residues, feed, manure, livestock and ponds in close proximity can be a source of microorganisms colonizing the farm compost when sufficient OM is present. In contrast, commercial composting takes place on a concrete floor. In addition, the smaller dimensions of farm compost windrows compared to commercial compost heaps allow more interaction with the farm environment. The more intensive process management at the farm results in more optimal moisture and temperature conditions compared to static pile composting at commercial facilities (Vandermaelen et al., 2025), possibly resulting in more microbial growth.

All bacterial and fungal biomass groups were correlated, indicating that factors influencing the total microbial biomass also influenced all subgroups in a similar way. Selective stimulation of subgroups did not occur. The contribution of fungi and mycorrhizae to the total microbial biomass was rather low (mean of both groups less than 10 %) and not explained by OM, composting practice nor feedstock group. However, feedstock and composting method can shift the communities within the fungal group (Neher et al., 2013). High-throughput sequencing used in the study of Neher et al. (2013) can however only assess relative changes in communities, in contrast to the PLFA analysis used in this study where absolute numbers of microbial biomass can be attained. Bacteria and fungi do not seem to be competitive in their abundance (biomass), instead they fluctuate in a similar way to the factors investigated here.

4.4. Cation exchange capacity

Measured CEC values in composts varied 4-fold between 17 and 68 $\text{cmol}_c\ \text{kg}^{-1}$. Similar CEC values at the high end of this range were measured for a small number of composts at different stages during composting, but comparisons of absolute values are difficult since different CEC measurement method were used (Harada and Inoko, 1980; Jimenez and Garcia, 1989; Kong et al., 2024; Smith and Hughes, 2004). Compost CEC values were in general larger compared to soil CEC values (Torrent et al., 2015). This difference in CEC is probably related to the difference in OM content of compost versus soil, and was also reflected in the increased CEC at larger compost OM content.

Both the organic matter and the mineral part of compost can contribute to the CEC. Especially the humified organic matter, present in mature compost, has functional groups contributing to CEC of compost (Bernal et al., 2017; Kong et al., 2024). The CEC of the mineral part can be attributed to the negative charge of clays and (if present) oxy-hydroxides (White, 1997). The positive intercept of Fig. 4 points to the contribution of mineral parts to the CEC. However, the overall increase of CEC with increasing OM content, and consequently decreasing mineral part, indicates that OM is the major CEC contributor.

The CEC over OM ratio varied more than 3-fold indicating some unexplained variation in the negative charge per unit OM. Part of this variation is explained by the stability or maturity of the compost, as reflected by the OUR (Fig. 5) or the NO_3^- over NH_4^+ ratio (Bernal et al., 2017). The CEC itself was not correlated to the compost stability, contrary to the observation of Harada & Inoko (1980) who analysed CEC during two cases of compost processing. For indicators used on a range of composts as end products, the CEC itself has a low accuracy (Kong et al., 2024), and the ratio of CEC over OM or OC may be the better choice as a maturity or stability indicator (Bernal et al., 1998). The more stable or mature composts are, the more negative charge the OM in these composts have because of the formation of humic-like substances, containing carboxyl and phenolic functional groups (Gajalakshmi and Abbasi, 2008; Kong et al., 2024).

4.5. Nutrient content

The content of N and P increased with compost OM content. Most of N is organically bound in compost. In contrast, a large part of P in compost is present in mineral form (Gagnon et al., 2012). But despite the major presence of P in Ca-P compounds in composts, P availability in compost can still be enhanced by OM content (Frossard et al., 2002). This effect of OM content, regardless of the feedstock group, is smaller for P than for N (Fig. 6 and supplementary information), probably because of the relatively smaller organic P than organic N fraction in composts. Significant correlations between nutrient contents were observed for the composts. This was also, but to a lesser extent, observed for Swiss composts (Kupper and Fuchs, 2007) indicating that the driving factors for nutrients in compost, i.e. the nutrient content of the feedstock and the OM content, are similar for the different compost nutrients.

Regardless of the OM content, composts from the green feedstock group had lower N and P contents compared to the more nutrient rich fvg and manure group composts. This can be explained by the lower N and P contents in garden and park residues than in fruit, vegetable and garden waste and manure. Also in other studies larger N or P contents were found in manure composts compared to composts from other feedstocks (Bernal et al., 2017; Faverial et al., 2016; Kupper and Fuchs, 2007). If nutrient delivery is an important goal for the intended compost use, fvg and manure composts are the better choice. However, care should be taken for immature composts that can induce mineral N immobilization especially when intended for use in growing media, resulting in mineral N shortage for the crop (Vandecasteele et al., 2021). Phosphorus is often less preferred than N, especially on P-rich fields with strict application limits common in Northwestern Europe (Amery et al., 2021), making low P composts a preferable option. The large range in nutrient contents in the current study, e.g. up to 11-fold for K, underlines the importance of measuring nutrient contents in composts to select the most appropriate use as growing media, soil improver, fertilizer or other application. Composts high in K content could be an excellent choice for e.g. fruit production.

5. Conclusion

A large range of chemical, biological and physical compost characteristics were measured by one laboratory on 107 composts from varying feedstocks, composting practices and countries in the North Sea Region. The resulting dataset gives an overview of compost characteristics and determining factors for these. Compost properties vary widely, which underlines the importance of measuring characteristics to select the intended application.

The observations in this dataset provide information on compost quality and composition in relation to composting practices (farm versus commercial) and feedstock composition, useful for benchmarking. Additionally, the origin was a significant factor, as composts from Belgium exhibited higher organic matter content compared to those from the other North Sea Region countries. The OM content of composts proved to be of major importance for microbial biomass in compost, CEC and nutrient content. As a result, the OM content of a stable or mature compost is a first good indicator of the compost quality. Instead of focusing on possible negative aspects of compost use due to contamination, more attention should be given to positive aspects of compost quality and resulting positive effects of compost use in soil and growing media. Further work should investigate how the variability in compost characteristics may influence soil health.

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CRediT authorship contribution statement

Fien Amery: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Paul Quataert:** Software, Methodology, Formal analysis, Data curation. **Elke Vandaele:** Resources. **Hans Smeets:** Resources. **Hanne Lakkenborg Kristensen:** Writing – review & editing, Resources, Funding acquisition. **Kenneth Loades:** Writing – review & editing, Resources. **Ina Körner:** Resources. **Koen Willekens:** Writing – review & editing, Supervision, Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.115259.

Data availability

The complete dataset is available on Zenodo (Amery et al., in press).

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