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Clustering of Exogenous Organic Material Properties to Improve Their Efficient Recycling in European Agriculture

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ABSTRACT

Exogenous organic materials (EOMs) are increasingly used as substitutes for mineral fertilizers and as tools to restore soil health within a circular bioeconomy context. However, the great diversity of EOMs in terms of origin, composition, chemical properties, and contaminant concentrations challenges their safe and efficient use in agriculture. The aim of the study was to establish a framework for the clustering of EOMs properties from several EU countries, enabling their categorisation according to their origin, characteristics, and chemical properties and trace elements (TE) profile. For that purpose, a dataset with chemical characteristics and TE concentrations from 118 EOMs was constructed from a database previously published. The EOMs included a wide range of organic residues and waste streams from agricultural, industrial, and urban origins representative of the diversity of European EOMs. Clustering analyses were carried out to distribute EOMs among clusters (i) of chemical properties based on their characteristics (dry mass, C-to-N ratio, pH, and concentrations of organic C, N, $N{-}NH_4$, P, K, Ca, and Mg), and (ii) of TE profile based on their concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn. Five practical scenarios of EOMs applications mixing amending and fertilizing EOMs were considered to estimate input fluxes of C, N, P, K, and TEs over a period of 10 years in contrasted areas (agricultural settings and peri-urban areas). The present study clustered the EOMs according to their soil improver characteristics that is, from NK fertilizing to liming and organic amending properties. The clustering analysis on TEs classified EOMs according to their TE profiles, with (i) smaller concentration of TEs (i.e., three quarters of EOMs), and (ii) larger concentration of all TEs and especially for Cu and Zn. The various practical scenarios simulating the repeated applications of local EOMs from contrasted areas showed that input fluxes were in line with commercial organic fertilizer inputs and below the goal of 170 kg N per hectare per year, while TE input fluxes respected the French regulation thresholds, even in the scenarios including EOMs containing also greater TE levels.

1 | Introduction

To ensure the security of future food production, it is essential to prioritise the maintenance of soil health and fertility by implementing sustainable practices that utilise bioeconomy to mitigate the impact of agriculture on the environment and the climate practices (Kopittke et al. 2019; FAO 2023). In addition to the imperative for increasing food production, it is also crucial to ensure the availability of adequate essential nutrients (micro- and macronutrients) to meet dietary requirements (Martinez-Ballesta et al. 2010). In sustainable agricultural practices, soil health indicators (i.e., the main soil qualities) notably of nutrient availability and retention capacity are closely associated with the maintenance of soil organic carbon concentration, which has traditionally been supported through the application of livestock manure in

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Highlights

- Exogenous organic materials (EOMs) were distributed into fertilizing and amending clusters.
- Urban EOMs contained higher trace element concentrations.
- Scenarios mixing amending and fertilizing EOMs were in line with inputs from commercial organic fertilizer.
- Scenarios mixing EOMs from urban origin remained below limit values for TEs.

livestock-producing areas (Peltre et al. 2011; Houot et al. 2014; EU 2024; FAO 2025). However, in the modern era, other organic materials derived from agricultural, industrial, and urban activities could be more extensively employed in soil applications when their safety is warranted (Lashermes et al. 2009).

Exogenous organic materials (EOMs) are secondary raw materials that is, wastes and residues from agriculture, municipalities or industries (Moinard et al. 2021), which are used as such or further processed with a variety of technologies to bio-based fertilizers or soil improvers (Kacprzak et al. 2022; Kurniawati, Stankovics, et al. 2023). Livestock manure represents about 90% of the total EOM amounts produced and used in France (Houot et al. 2014). The growing global population has led to the production of vast quantities of organic solid waste from urban and industrial activities, due to the implementation of environmental regulation and waste management technologies (Lopez-Rayo et al. 2016; Sharma et al. 2017). Over the last decades, the diversity of EOMs has increased, as they are produced by processing a wide range of waste materials via different technologies. The origin of the input materials, the processing steps, and the parameters involved (e.g., temperature, retention time, and pH), all influence the characteristics of the end-products that is, EOMs (Guilayn et al. 2019; Chojnacka et al. 2024). In addition to their agronomic properties, EOMs can contain various contaminants, depending on the origin of the raw materials and the treatments they have undergone, including pathogens, trace elements (TE), and organic contaminants (Kupper et al. 2014; Bourdat-Deschamps et al. 2017; Michaud et al. 2020; Munoz et al. 2021; Kurniawati, Toth, et al. 2023). Of the TEs, some are essential plant nutrients, such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn), which can be deficient in some agroecosystems, such as Cu, Fe, and Zn in calcareous soils (Kirkby and Römheld 2004; Michaud et al. 2007; Moreno-Jiménez et al. 2016; Asadu et al. 2024). The input of EOMs to soil has been demonstrated to serve as a source of micronutrients, which may potentially result in biofortification (McGrath et al. 1995; Bolan et al. 2021). However, if concentrations of essential TEs in soils are high, they can impair the proper functioning of the soil by becoming phytotoxic or toxic to the soil organisms, notably for Cu and Zn (Michaud et al. 2007; Kirchmann et al. 2017). Besides those micronutrient TEs, the majority of concern refers to the toxic elements cadmium (Cd), mercury (Hg), lead (Pb), and the metalloid arsenic (As) (Alloway and Jackson 1991; Kabata-Pendians 2012). Among these toxic TEs, Cd is of particular concern due to its high toxicity, carcinogenicity, and high dietary intake through crop contamination, especially cereals (Viala et al. 2017; Tian et al. 2018; Grüter et al. 2019). In fact, EOMs can represent a source of Cd; nevertheless, its main entrance into soils comes from mineral P fertilizers (Sterckeman et al. 2018; Michaud et al. 2020). EOMs are nutrient-rich materials that may be contaminated, meaning that their impact on fertilization efficiency, soil health, and the environment can vary considerably between different EOMs; for example, sewage sludge is known to contain high levels of nutrients, as well as potential contaminants (Bolan et al. 2021; Levine et al. 2023).

Conventionally, EOMs are classified according to empirical criteria such as type of raw materials (e.g., slurry, farmyard manure, sludge) and process technologies (e.g., digestates, composts) (Morvan et al. 2006; Michaud, Van Der Smissen, et al. 2025). The EU Fertilizer Regulation EU 2019/1009 classifies EOMs based on two categories, the Product Function Category (PFC) and the Component Material Category (CMC) (EU 2019). PFC includes fertilizers, liming materials, soil improvers, growing media, inhibitors, plant bio-stimulants, and product mixtures, while CMCs include virgin raw materials and their mixtures (i.e., plants, plant parts, extracts; compost; crop digestates and other digestates; food industry by-products; micro-organisms; nutrient polymers; other polymers; materials produced from animal by-products). The product, which complies with the safety requirements specified for the CMC categories, can be CE marked and placed on the EU internal market. In addition to CE marked products, fertilizer products marketed domestically may be manufactured in accordance with the requirements of national fertilizer legislation, resulting in a wide variety of different EOMs being produced and used within the EU. In a perspective of circular bioeconomy, managing recycling in agriculture of such EOMs must be cost-effective, with high fertilizer/amending value, and with safe and clean products (Kirchmann et al. 2017; Sharma et al. 2017; Tampio et al. 2022). Additionally, improper use of EOMs can result in nutrient over-fertilisation and losses in the environment (O'Connor et al. 2022). The farmers using the EOMs and agricultural advisers might not have enough knowledge on the products, their market availability, or composition (Hijbeek et al. 2019; Moinard et al. 2021). It is therefore necessary to propose guidelines and best practices recommendations for farmers (as proposed in Kurniawati, Toth, et al. 2023), notably by providing a holistic analysis and clustering of the EOMs properties diversity based on chemical properties and contaminant risks.

A few previous classification studies on EOMs have been published focusing on some raw materials, processes, carbon (C) and nitrogen (N) value or contaminant context. In France, previous studies published multifactor approaches to establish C and N classifications for sewage sludge (Parnaudeau and Dignac 2007), animal wastes (Morvan et al. 2006), and industrial wastewaters (Parnaudeau et al. 2006). Other studies predicted the availability of C and N with statistical and modelling approaches with the aim of providing decision-making tools for a diversity of EOMs (Lashermes et al. 2009, 2010; Peltre et al. 2011; Levavasseur et al. 2022) and digestates (Guilayn et al. 2019; Fernández-Domínguez et al. 2021). Additionally, the presence of contaminants has been analysed in several studies. For instance, Kupper et al. (2014) studied

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161 compost samples from Switzerland and analysed the effects of treatment process and input materials on TEs. Munoz et al. (2021), Saliu et al. (2024) and Michaud, Dunsin Saliu, et al. (2025) also analysed the emerging poly- and perfluorinated substances levels for various EOMs and their inputs to agricultural soils.

Despite the extensive research done on different EOMs, their characteristics and use, there is a lack of publicly available databases, characterisation studies that deal with a wide range of EOM characteristics and EOM types notably in EU (Perez-Mercado et al. 2024; Michaud, Van Der Smissen, et al. 2025). A better characterisation of EOM properties, including chemical characteristics and trace elements concentrations, for a large diversity of EOMs is needed to better qualify the variability and the clustering of the properties in European EOMs. This is essential to ensure the efficient recycling of these products and the recovery of their nutrients, in diverse climatic and soil conditions, and to make national policy recommendations. The aim of the study was to establish a framework for the clustering of EOMs properties from several EU countries, enabling the categorisation of these materials according to their origin, description information, and chemical properties or trace elements profile.

2 | Materials and Methods

2.1 | Dataset

The data was collected from a database of 126 EOMs established from available national sources from six European countries (Belgium, Finland, France, Italy, Lithuania, and The Netherlands) as described in Michaud, Van Der Smissen, et al. (2025). In the present study, a dataset was constructed from this published database by calculating averages for each characteristic per EOM type for 118 EOMs for which data have been registered according to the following dataset requirements, so that eight EOMs have been deleted from the published database. The data included dry mass content (DM, expressed based on fresh matter [FM]) and the following chemical characteristics expressed as normalised on a dried matter basis: C to N ratio (C/N), pH, organic C (org. C), total nitrogen (N), ammonium N ($N—NH_4$), total potassium (K), total phosphorus (P), total calcium (Ca), total magnesium (Mg), total arsenic (As), total cadmium (Cd), total cobalt (Co), total chromium (Cr), total copper (Cu), total mercury (Hg), total nickel (Ni), total lead (Pb), total zinc (Zn).

The EOMs included a wide range of organic products from agricultural, industrial, and urban origins (Table 1) representative of the diversity of EOMs applied to European cultivated soils. The EOM denomination was established according to the methodology presented in Michaud, Van Der Smissen, et al. (2025) with affiliation of each EOM according to its origin, end-product type after process, major raw material, specification, and dry mass class (See SI1.1 for detailed list of EOM denominations). Of the 118 EOMs and based on their origin, 8% refers to agricultural crops/residues, 15% to industrial EOMs, 48% to livestock manure, 13% to other/mixed EOMs, and 25% to urban EOMs. Considering the end-product types, 35% concerned unprocessed EOMs, 33% digestates, 18% composts, 7% composted digestates, 3% limed EOMs, 2% dehydrated EOMs, 1% biochars, aerobically stabilized EOMs, and mineral concentrates. The main major raw materials of the EOMs were manure with 27% of EOMs, slurry and sewage sludge with 12% of EOMs each, and plant material for 10% of EOMs; considering that the major raw material slurry refers to the liquid part of the animal faeces, while manure refers to the solid part of the animal faeces often mixed with straw, and both are considered as livestock manure.

2.2 | Clustering of the EOM Properties

An integrative multivariate approach was carried out to capture the overall chemical signature of the EOMs using the most commonly referenced chemical parameters in the literature (DM, C, N, C/N, pH, $N—NH_4$, P, K, Ca, and Mg) and the main of the TEs considered in regulations (As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn). First, Principal Component Analysis (PCA), which is a robust multivariate approach that efficiently handles correlated variables and reduces dimensionality while preserving the main variance structure, has been carried out to summarize correlations and reveal the main compositional gradients across EOMs. Secondly, Ascending Hierarchical Clustering (AHC) analysis, which is an integrative multivariate approach, allowed grouping EOMs according to their overall properties and interpreting their chemical and TEs profile in a typological framework.

Two complementary multivariate analyses combining PCA and AHC were carried out on two sets of characteristics with: (a) the following chemical properties—DM, C/N, pH, org. C, N, $N—NH_4$, P, K, Ca, and Mg—studied on the 118 EOMs considered for the clustering analysis; (b) the following TEs—As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn—studied on 72 EOMs considered for the clustering analysis. Those variables were selected to represent usual chemical properties and TE aspects, with consideration also given to data availability in the dataset to minimize the proportion of missing values; that is, each variable was selected to have a missing value rate less than 30% (except for Ca and Mg), with missing data inferior to 10% for DM, C, N, P, K, Cd, Cr, Cu, Ni, Pb, and Zn (Table 2). In multivariate analyses, the complete dataset is considered, here with the remaining missing values imputed using the nearest neighbour methodology, which replaces missing values by values from similar observations for which all the information was observed (Glasson-Cicognani and Berchtold 2010).

Additional C and N agronomic properties were represented as a function of the clusters of chemical properties depending on the availability of the data, as follows: index of remaining organic carbon (IROC) ($n=29$ EOMs), mineralized carbon after 91 days of mineralization expressed in percentage of organic carbon ($n=30$ EOMs), ratio of $N—NH_4$ over N ($n=76$ EOMs), and potentially mineralized nitrogen after 91 days of mineralization expressed in percentage of organic nitrogen ($n=25$ EOMs).

2.3 | Input Flux Calculations

The inputs of C, N, P, K, and TEs resulting from the repeated EOM applications were calculated by multiplying the element

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TABLE 1 | Description of the EOMs considered in the dataset with the following data presented: origin of EOMs, end-product after process, major raw material and related number of EOMs (*n*).

Origin	End-product	Major raw material	*n*
Agricultural crops/residues	Composted digestate	Unspecified	1
	Digestate	Cover crop, plant material, unspecified	6
	Unprocessed	Mix, plant material	3
Industrial	Aerobic stabilized	Sludge	1
	Compost	Slurry	1
	Dehydrated	Vinasse	1
	Digestate	Unspecified	2
	Limed	Sludge	2
	Unprocessed	Plant material, sludge	11
Livestock manure	Biochar	Manure	1
	Compost	Manure, slurry	9
	Composted digestate	Manure, mix, slurry	3
	Digestate	Manure, mix, slurry	15
	Mineral concentrate	Slurry	1
	Unprocessed	Manure, slurry	19
Other/mixed	Compost	Animal by-product, mix, plant material, unspecified	4
	Digestate	Animal by-product, mix, plant material, unspecified	8
	Unprocessed	Animal by-product	1
Urban	Compost	Green waste/biowaste, residual municipal solid waste, sewage sludge, source-sorted biowaste	7
	Composted digestate	Residual municipal solid waste, sewage sludge, source-sorted biowaste	4
	Dehydrated	Sewage sludge	1
	Digestate	Mix, residual municipal solid waste, sewage sludge, source-sorted biowaste	8
	Limed	Sewage sludge	2
	Unprocessed	Sewage sludge, source-sorted biowaste, urine	7

concentration and a fixed amount of EOM on a fresh matter basis per application over 10 years.

First, the EOM applications considered two single agronomic goals to estimate related TE input fluxes: EOMs were used as a substitute to mineral N fertilizer, with inputs every year according to the goal of 170 kg of N per hectare (EU 1991); EOMs were used as a substitute to mineral P fertilizer added every year according to a goal of 17 kg of P per hectare (Denoroy et al. 2019).

Secondly, input fluxes of C, N, P, K, and TEs over 10 years were calculated for five practical scenarios of EOM applications mixing local amending and fertilizing EOMs, which considered the objective of 170 kg N per hectare per year (EU 1991) and agronomical rates of EOM application. Those practical scenarios corresponded to contrasted areas producing EOMs, as presented below:

- Scenario "Cattle farms": cattle farm areas, with applications of EOMs in the form of cattle slurry and manure, which represent usual combination in agricultural settings;
- Scenario "Pig farms": pig farms areas, with applications of two digestates of pig slurry varying in their dry mass;
- Scenario "Cereal farms" (prospective): large cereal farms in areas without livestock farms and surrounded by moderate sized cities and industries, with applications of EOMs as digestate of cover-crop mixed with amendments composed of local urban and industrial wastes such as mill sludge and compost of sewage sludge;

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TABLE 2 | Description of the dataset with the following data presented: characteristics considered in the clustering analysis (Char.), unit, number of EOM per characteristic (*n*), frequency in the EOM dataset (Freq.), minimum (min.), maximum (max.), median (med.), mean; results from Kruskall-Wallis test evaluating characteristics variation as a function of EOM description information.

Char.	Unit	*n*	Freq.	Min.	Max.	Med.	Mean	Origin	End-product	Major raw mat.	%DM
DM	% FM	118	100%	1.1	98.9	28.1	33.5	ns	***	ns	***
pH	—	94	80%	5.9	12.8	8.1	8.3	ns	*	ns	ns
C/N	g/g	83	70%	0.7	38.2	10.4	11.7	ns	**	*	***
Org. C	g/kg DM	111	94%	64.6	623.3	315.9	301.2	***	***	**	*
N	g/kg DM	116	98%	0.8	536.4	29.2	46	**	**	**	***
$N—NH_4$	g/kg DM	102	86%	0	463.6	6.6	20.7	**	***	*	***
P	g/kg DM	114	97%	0.5	47.5	10.9	12.8	*	ns	***	*
K	g/kg DM	109	92%	0.2	218	18.1	28.1	***	*	***	***
Ca	g/kg DM	78	66%	4.1	373.4	31.6	60.8	***	**	***	*
Mg	g/kg DM	81	69%	0.3	58	6.4	9	ns	ns	ns	ns
As	mg/kg DM	56	47%	0	9.1	1.8	2.6	***	*	**	ns
Cd	mg/kg DM	65	55%	0.1	2.7	0.5	0.6	**	ns	**	ns
Cr	mg/kg DM	65	55%	1	268	13.6	23.1	***	ns	**	ns
Cu	mg/kg DM	72	61%	9.2	486	88.3	114.1	**	ns	**	ns
Hg	mg/kg DM	52	44%	0	1.88	0.111	0.299	ns	ns	*	ns
Ni	mg/kg DM	66	56%	2.1	67.5	13.7	15.5	**	ns	**	ns
Pb	mg/kg DM	66	56%	0.1	150.1	8.6	21.4	***	ns	***	ns
Zn	mg/kg DM	72	61%	22.8	1628.1	267.3	383.8	**	ns	**	ns

Note: FM (fresh matter), DM (dry matter); *p value < 0.05, **p value < 0.01, ***p value < 0.001, ns for non-significant.

- Scenario "Peri-urban": peri-urban areas, with production of high amounts of urban wastes processed and recycled in local cereal agricultural settings, with applications of EOMs as digestate and compost of source-sorted biowastes, and unprocessed and composted sewage sludge;
- Scenario "Peri-urban with urine" (prospective): peri-urban areas, with production of high amounts of urban wastes (un)processed and recycled in local cereal agricultural settings, with applications of EOMs as urine and composts of source-sorted biowastes and sewage sludge.

2.4 | Further Statistics

Statistics were performed using XLSTAT (V 2023.2, Addinsoft). Statistical significance was set at 5% in all analyses. The following statistical methods were used to explore differences between groups, identify significant associations, and support clustering analysis: the Kruskal–Wallis non-parametric test (to compare multiple groups) combined with bilateral Dunn's tests with Bonferroni correction (for pairwise comparisons), Spearman correlation matrices (to assess relationships between variables), and classification trees using the CHAID method (Chi-square Automatic Interaction Detection) for categorical prediction and variable interaction analysis to identify varying factors among clusters.

3 | Results and Discussion

3.1 | Short Description of the Dataset

The chemical characteristics were highly variable within the dataset (Table 2). The chemical characteristics that were reported most frequently were dry mass (reported in 100% of the data), with values ranging from 1.1% to 98.6% of fresh matter, and the concentrations of N (98%), P (97%), and organic C (94%), with values varying from 0.8 to 536.4 g N/kg DM, 0.5 to 47.5 g P/kg DM and 64.6 to 623.3 g C/kg DM, respectively. The largest N concentration corresponded to the urban unprocessed urine which exhibited far greater N concentrations compared to the other EOMs, with 536 and 464 g/kg, respectively for N and $N—NH_4$, as previously observed (Moinard et al. 2021; Martin et al. 2023). In fact, this EOM was found as an outlier, which was excluded from the PCA and AHC, so that 117 EOMs were finally considered in the PCA and AHC. The correlations between chemical characteristics showed that K and N concentrations (total, $N—NH_4$) were positively correlated with correlation coefficients over 0.6 and p value < 0.001, while C-to-N ratio and dry mass were

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negatively correlated to the N concentrations (total, N—NH_4) with correlation coefficients inferior to −0.6 and p value < 0.001 (See Appendix SI1.2). Cu and Zn, which were the most frequent TEs with registered values in the dataset, also had the greatest concentrations, with values varying from 9.2 to 486.0 mg/kg DM and from 22.8 to 1628.1 mg/kg DM, respectively. The correlation matrix showed that As, Cd, Cr and Pb had correlation coefficients superior to 0.50 and p value < 0.001 (See Appendix SI1.2). Ni presented correlation coefficients with Cr and Pb over 0.50 and p value < 0.001. Cu and Zn were highly correlated with a correlation coefficient of 0.86 (p value < 0.001), with correlation to the other TEs (r < 0.50). An outlier was identified with industrial unprocessed sludge of leather and fur industry for which Cr concentration was far superior to the other EOMs with 268.0 mg/kg DM, which was excluded from the PCA and AHC (i.e., 71 EOMs finally considered); this EOM is authorised for spreading according to Belgium regulation (BE 1995). Such order of magnitudes and correlations are consistent with previous studies (Morvan et al. 2006; Lashermes et al. 2009, 2010; Houot et al. 2014; Tampio et al. 2016; Alvarenga et al. 2017; Michaud et al. 2020; Caradec et al. 2025).

The chemical characteristics varied according to the EOM description information that is, origin, major raw material, end-product after process, and dry mass class (Table 2; See also detailed box-plots in SI1.3). Briefly, considering the origins of EOMs, livestock manure EOMs exhibited greater organic C and K concentrations, industrial EOMs exhibited larger Ca concentration; urban EOMs exhibited larger concentrations of As, Cd, Cr, Cu, Ni, Pb and Zn, while livestock manure and crops/residues EOMs exhibited greater concentrations of Cu and Zn. Of the end-products, composts and composted digestates exhibited larger dry mass classes, digestates and unprocessed EOMs larger N concentrations (total, N—NH_4) and limed EOMs greater Ca concentration. Of the major raw materials, sewage sludge showed larger P concentrations, sludge and plant materials greater Ca concentrations, while urine exhibited the largest N concentrations (total, N—NH_4). Sewage sludge exhibited superior concentrations of As, Cd, Cu, Ni, Pb and Zn, and residual municipal solid wastes larger As, Cd, Cr and Pb concentrations. Finally, the dry mass class influenced significantly some chemical characteristic values, with C-to-N ratio smaller in 0%–15% DM class compared to the other DM classes (i.e., > 15% DM), and concentrations of K and N (total, N—NH_4) greater in 0%–15% DM class compared to the other DM classes (i.e., > 15% DM). Such results showed that chemical properties varied according to all the EOMs description information (i.e., origin, end-product, major raw material, dry mass class), while TE concentrations varied more according to the origin and the nature of major raw materials.

The present results align with previous studies showing variation of characteristics among: (i) EOM groups or end-product types (Morvan et al. 2006; Lashermes et al. 2009, 2010; Tampio et al. 2016; Guilayn et al. 2019); (ii) major raw materials with sewage sludge exhibiting larger concentrations of P and urine far larger levels of N (Moinard et al. 2021; Martin et al. 2023; Perez-Mercado et al. 2024); (iii) dry mass classes with N and K predominantly found in the 0%–15% DM class that is, liquid fractions (Caradec et al. 2025); (iv) superior TE concentrations in urban EOMs, especially sewage sludge (Sharma et al. 2017; Michaud et al. 2020; Bolan et al. 2021). In addition, beyond these group-level trends, the detailed boxplots by individual elements (See SI1.3) show that intrinsic variability remains within and between origins, dry-mass classes, processing types and composition, with substantial overlaps between groups. As a result, the interpretation for such of group-levels of EOMs is challenging. This complexity, therefore, supports the need for an integrative multivariate approach to better capture combined compositional patterns of EOMs.

3.2 | Clustering of the Chemical Properties

Previous studies involving fewer EOM types (Parnaudeau et al. 2006; Morvan et al. 2006; Parnaudeau and Dignac 2007; Lashermes et al. 2009, 2010; Levavasseur et al. 2020, 2022) used C and N concentrations to classify EOMs according to their C and N values. For the first time, the present study proposes a clustering of the chemical properties for a broad range of EOMs from multiple origins based on a comprehensive set of usual characteristics that is, DM, C-to-N ratio, pH, and concentrations of organic C, N, N—NH_4, K, P, Ca, and Mg.

Figure 1 presents the projection of the chemical set of characteristics for the 117 EOMs, with representation of the observations (i.e., EOMs) according to their dry mass class. The first two component factors accounted for 55.9% of total variance. The first component discriminated EOMs with high N and K concentrations (right side) from those with high DM and C-to-N ratios (left side). The second component separated EOMs with high Ca, Mg, and P (upper part) from those with high organic C concentration (inferior part). EOMs exhibiting a dry mass smaller than 15% of fresh matter were in the extreme right part of the PCA and characterised by greater concentrations of N, N—NH_4, and K. The major raw materials which were represented as Supporting variables were departed as follows: cover crop, slurry, unspecified, mix, and animal by-product in the right part of the PCA suggesting larger concentrations of N, N-NH_4, and K, while green waste, biowastes, municipal solid wastes, sludge, and plant materials were in the left part of the PCA suggesting EOMs composed by those major materials exhibiting smaller concentrations of N, N-NH_4, and K and greater dry mass and C-to-N ratios.

The ascending hierarchical clustering analysis defined four distinct clusters of EOMs presented in detail in Appendix SI2, with the related variation of chemical properties represented as box plots in Figure 2. The main part of the EOMs was gathered in Clusters 1 and 3 (39 EOMs and 54 EOMs, respectively) and corresponded principally to livestock manure and urban EOMs, with a majority of composts and unprocessed EOMs in Cluster 1 (59% and 21%, respectively), and digestates and unprocessed EOMs in Cluster 3 (43% and 41%, respectively). Those EOMs exhibited larger dry mass, greater organic C concentration (Cluster 3), and smaller NK concentrations compared to the EOMs from Cluster 2. The 18 EOMs from Cluster 2, which exhibited the largest N and K concentrations, were mainly agricultural digestates and unprocessed EOMs (67% and 28%, respectively) with dry mass inferior to 15% of the fresh matter. In fact, Cluster 3 contains some agricultural solid digestates and unprocessed livestock

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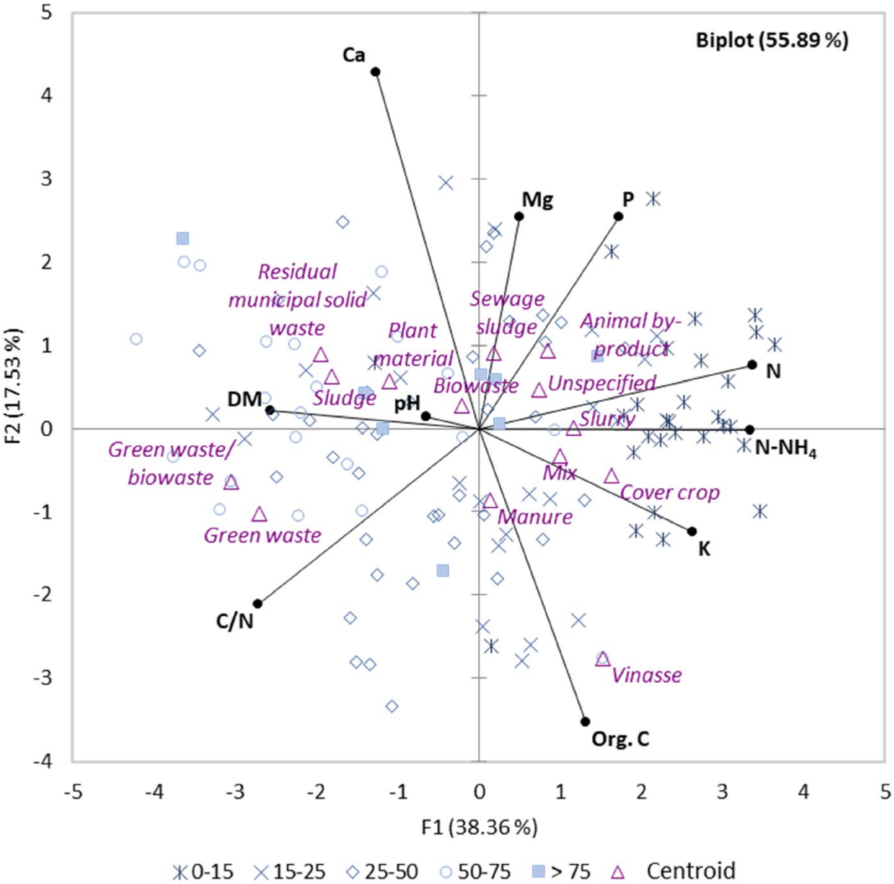

FIGURE 1 | Principal component analysis of chemical properties, with the considered quantitative variables (DM, C/N, pH, and concentrations of organic C, N, N—NH_4, K, P, Ca, and Mg), major raw materials entering into the composition of EOMs considered as Supporting variables (centroids represented as triangles), and individuals represented according to their class of dry mass (0%–15%, 15%–25%, 25%–50%, 50%–75%, and superior to 75% of fresh matter).

manure which are fibrous types of EOMs (SI2.2), whereas Cluster 2 contains mainly raw and liquid digestates (0%–15% DM) with larger N—NH_4 concentration, which is typical of digestates (Guilayn et al. 2019; Caradec et al. 2025). Finally, the 6 EOMs from Cluster 4 were industrial EOMs, which had, in majority, dry mass larger than 50% of fresh matter, the largest C-to-N ratios, pH, and Ca concentrations, and the smallest concentrations of C, N, P, and K compared to EOMs from the other clusters.

In addition, Figure 3 presents the variation of additional C and N agronomic properties across the EOMs pertaining to those chemical clusters. Those C and N agronomic properties were excluded from the clustering analysis due to the lack of data in the dataset. Figure 3 showed that EOMs from Cluster 1 exhibited a significantly greater index of remaining organic C (IROC), which represents the potential of organic carbon storage after incorporation into soil (Lashermes et al. 2009) and significantly smaller mineralized carbon after 91 days of incubation compared to the EOMs from Cluster 2 (Figure 3). This suggests that EOMs from Cluster 1, which are mainly composts, exhibited superior carbon amending values compared to EOMs from Cluster 2, which agreed with previous studies (Lashermes et al. 2009; Levavasseur et al. 2020). Figure 3 showed that the EOMs from Cluster 2 also exhibited significantly larger N—NH_4-to-N ratio (0.5–0.7) and larger median (but not significantly) of potentially mineralized organic N compared to EOMs from Clusters 1 and 3, which suggests that those EOMs had superior N fertilizing potential compared to the EOMs from Clusters 1 and 3.

Further classification trees were carried out to identify criteria driving the EOM affiliation to clusters of chemical properties. According to the EOM description information (i.e., origin, end-product, major raw material, DM class), dry mass classes were the first categorizing factor (SI2.3), while when considering the chemical properties, organic C concentration distributed at first the affiliation of EOMs to clusters followed by the dry mass, pH, and concentration of N—NH_4 (SI2.4), which agreed with the PCA and AHC analyses.

The clustering based on chemical properties confirms the partition of EOMs on a gradient of C and N contributions-from N fertilizing values to C amending values-on a wide diversity of EOMs recycled in various countries in the EU—pertaining to multiple origins, compositions, and processes— (Parnaudeau et al. 2006; Morvan et al. 2006; Parnaudeau and Dignac 2007; Lashermes et al. 2009, 2010; Levavasseur et al. 2020, 2022). Besides the number of EOM types, the originality of the present study lies in complementing previous approaches by considering an overview of usual chemical properties that take into account other characteristics beyond just N and C. Moreover, as

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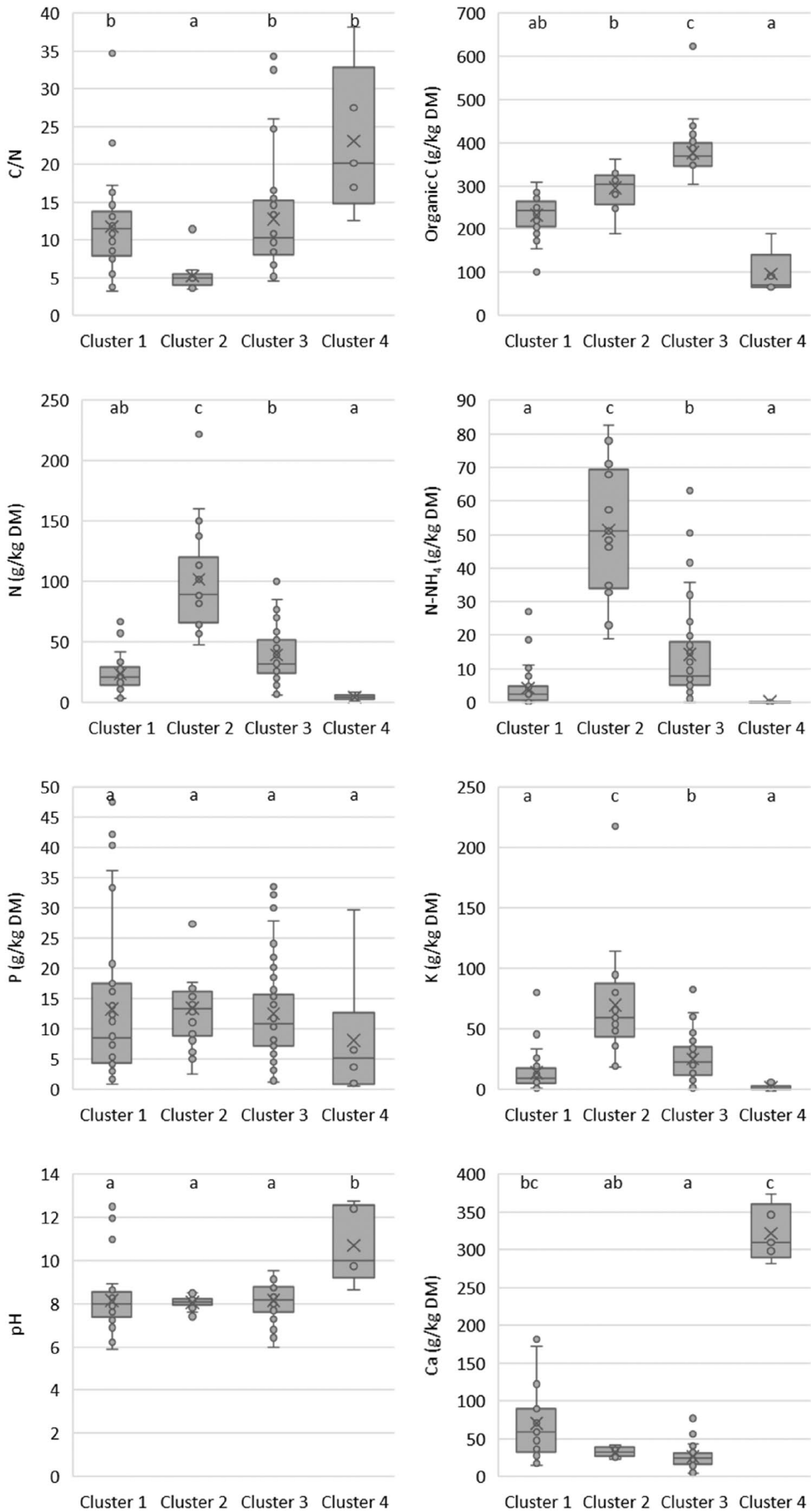

FIGURE 2 | Legend on next page.

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FIGURE 2 | Box plots of chemical properties according to the clusters of EOMs defined in the ascending hierarchical clustering analysis of chemical properties with the following data presented: C-to-N ratio, concentrations of organic C, N, N—NH_4, P, K, Ca expressed in grams per kilogram of dry mass (DM) and pH; means as crosses in boxes, median as the intermediate line of boxes, 25%–75% quartiles as upper/lower lines of boxes, 10%–90% quartiles as upper/lower vertical bars; abc letters stand for significant differences between clusters with Dunn's bilateral tests.

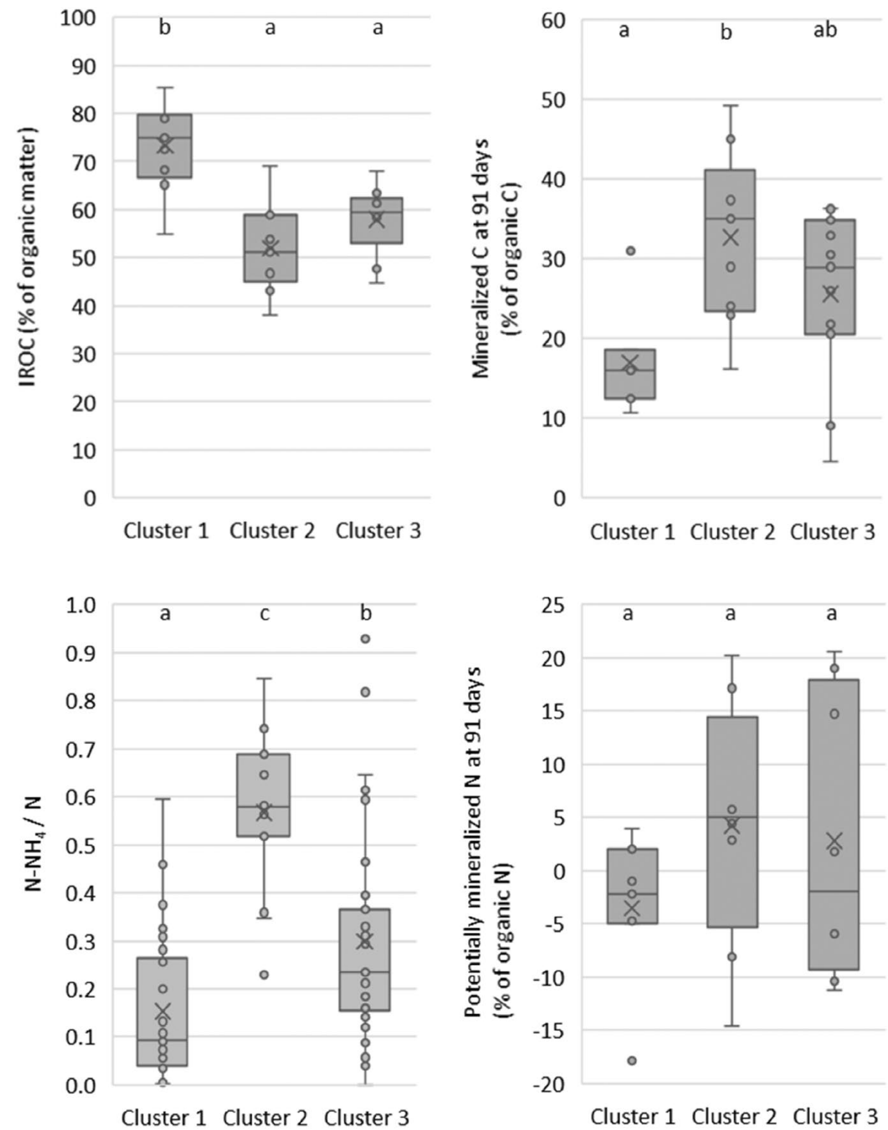

FIGURE 3 | Carbon and nitrogen agronomic properties variation according to the clusters of chemical properties with the following data available for clusters 1–3 (i.e., no data for Cluster 4): Index of remaining organic carbon (IROC) expressed in percentage of organic matter ($n=29$ EOMs), mineralized carbon after 91 days of mineralization expressed in percentage of organic carbon ($n=30$ EOMs), ratio of N—NH_4 over N ($n=76$ EOMs), and potentially mineralized nitrogen after 91 days of mineralization expressed in percentage of organic nitrogen ($n=25$ EOMs); means as crosses in boxes, median as intermediate line of boxes, 25%–75% quartiles as upper/lower lines of boxes, 10%–90% quartiles as upper/lower vertical bars; abc letters stand for significant difference between clusters with Dunn's bilateral tests.

mentioned earlier by Morvan et al. (2006) for animal wastes, the present clustering analysis revealed meaningful differentiation among intrinsically different EOMs, such as composts in Cluster 1, agricultural digestates composed primarily of plant materials and manure/slurry with dry mass smaller than 15% of fresh matter in Cluster 2, the other digestates and unprocessed manure in Cluster 3, and industrial EOMs with high pH and Ca concentrations in Cluster 4 (list of EOMs per clusters in SI2.2). It gathered both processed and unprocessed EOMs sharing the same major raw materials, such as unprocessed and processed manure with a few composts and digestates not included in Clusters 1 and 2 as well as biochar in Cluster 3, unprocessed and processed sewage sludge (compost, limed) in Cluster 1, and slurry digestates along with unprocessed slurry and slurry mineral concentrate in Cluster 2. In addition, this clustering of chemical properties grouped EOMs from different origins but with similar characteristics, such as digestates composed of urban biowastes, agricultural

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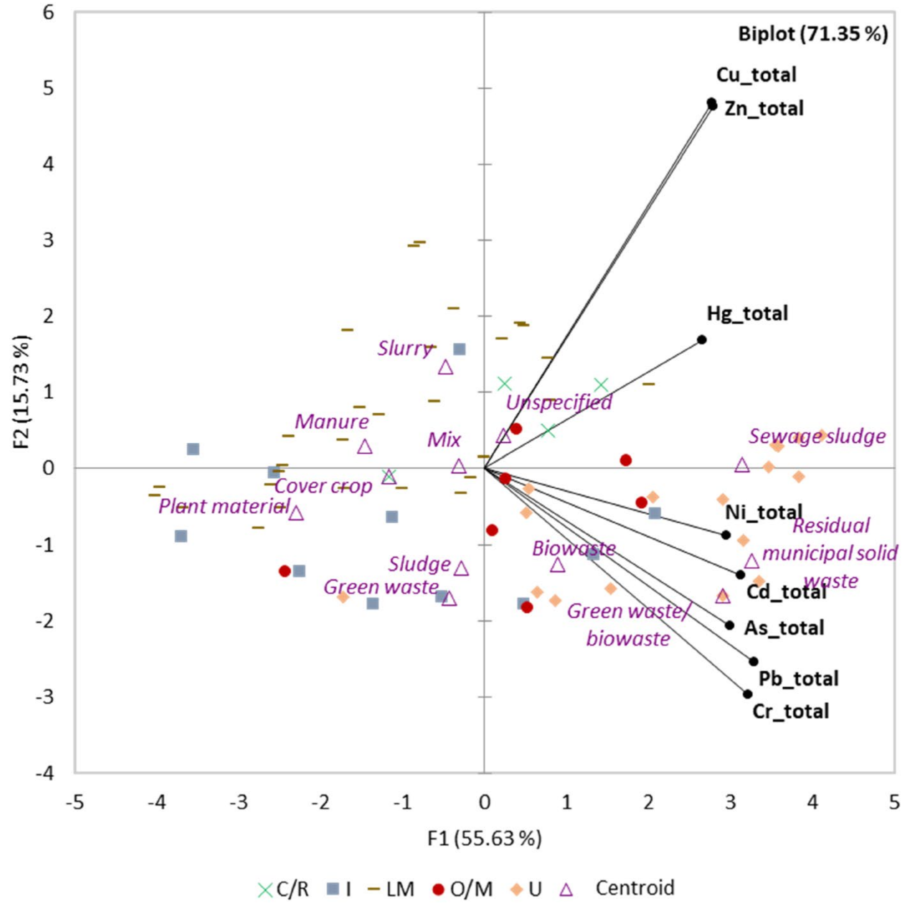

FIGURE 4 | Principal component analysis of trace elements concentrations, with the considered variables (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn), major raw materials entering into the composition of EOMs considered as Supporting variables (centroids represented as triangles), and individuals represented according to the origin (i.e., C/R—agricultural crops/residues, I—industrial, LM—livestock manure, O/M—other/mixed, U—urban).

plant material or cover crop, and livestock slurry in Cluster 2; urban composts of biowastes and green waste with composts of manures and composts from other/mixed origin in Cluster 1; urban sewage sludge with manures in Cluster 3.

3.3 | Clustering of the Trace Element Concentrations

The second clustering analysis aimed to distribute EOMs among classes of TE profile based on their concentrations of the following trace elements: As, Cd, Cr, Cu, Hg, Ni, Pb and Zn. Figure 4 shows the projection of TE set of values for the 71 EOMs for which TEs were registered according to the prerequisite of the clustering analysis. The first two component factors accounted for 71.3% of the total variance. The first component accounted for 55.6% of the total variance and separated EOMs with larger TE concentrations (right side) from EOMs with smaller concentrations (left side). The second component accounted for 15.7% of total variance and separated EOMs with larger Cu and Zn concentrations (upper part) from those with smaller concentrations (inferior part). Urban EOMs were mainly in the right part of the PCA in relation to greater concentrations of TEs. The centroid of the major raw materials of sewage sludge, residual municipal solid waste and green waste—biowaste were in the extreme right part of the PCA, suggesting greater concentrations of As, Cd, Cr, Hg, Ni and Pb in EOMs composed by those major raw materials compared to the EOMs composed by the other major raw materials. Livestock manure EOMs were mainly in the left part of the PCA, suggesting inferior TE concentrations, except for some livestock manure EOMs present in the upper right part of the PCA, suggesting larger concentrations of Cu and Zn as well as for some crops/residues EOMs.

The ascending hierarchical clustering analysis defined two clusters of EOMs presented in Figure 5 (see also the list of EOMs in Appendix SI3), which differed as follows:

- Cluster A: larger concentrations for all TEs, with medians of 2.4, 1.0, 31.0, 263.4, 0.6, 21.4, 41.5, and 845.3 mg/kg DM, respectively for As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn;
- Cluster B: smaller concentrations of TEs compared to the EOMs from cluster A, with medians of 1.7, 0.5, 11.8, 61.5, 0.1, 12.4, 5.3, and 208.5 mg/kg DM, respectively for As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn.

The cluster B gathered 56 EOMs of the 71 EOMs considered in the TE clustering analysis from all origins with 25 livestock manure EOMs, 10 urban EOMs, 11 industrial EOMs, 7 other/

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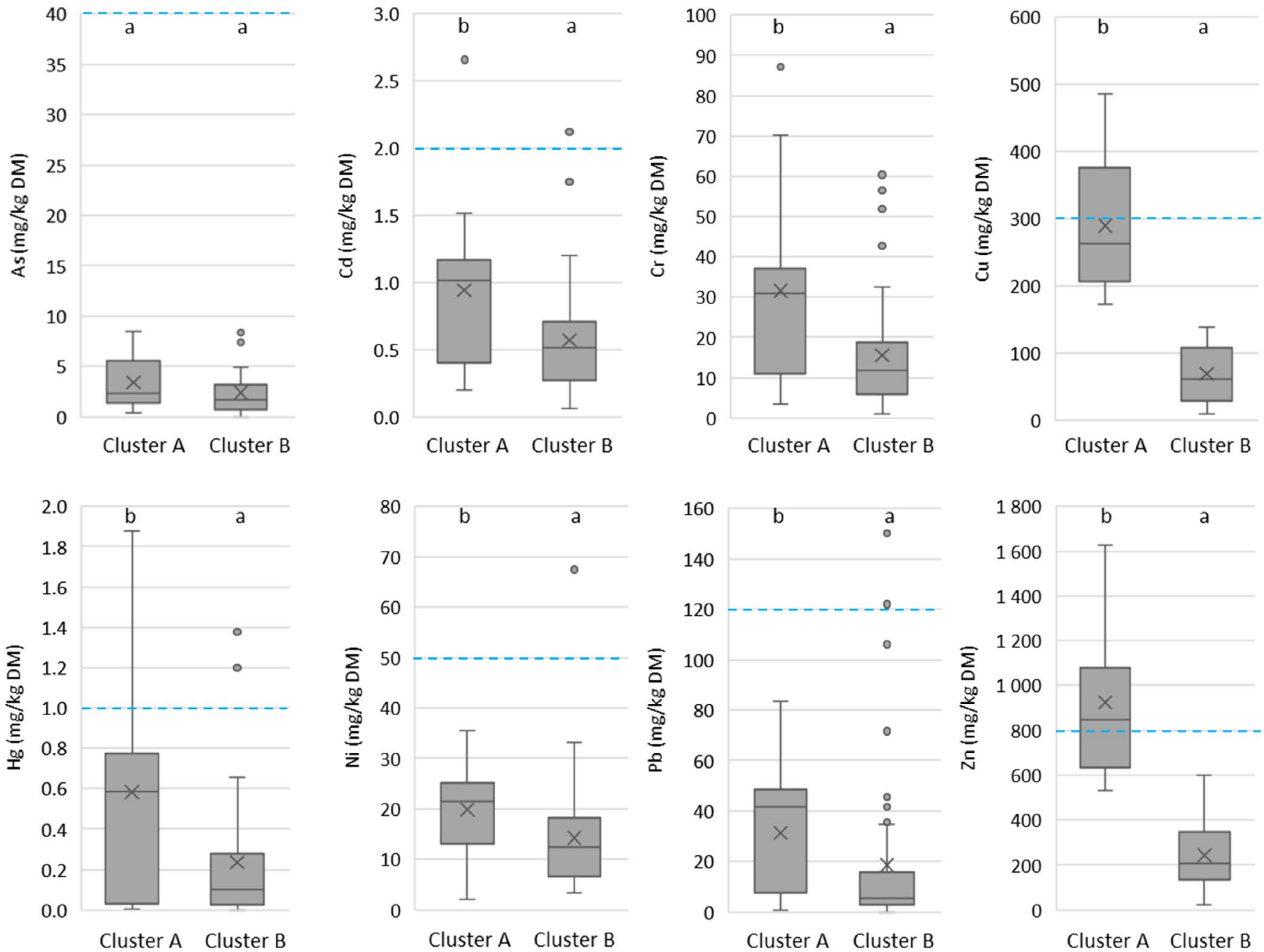

FIGURE 5 | Box plots of trace elements concentrations of EOMs according to clusters defined in the ascending hierarchical clustering analysis, and the European regulations with: As, Cd, Cr, Cu, Hg, Ni, Pb and Zn expressed in mg/kg of dry mass (DM); UE regulations as blue line; means as crosses in boxes, median as intermediate line of boxes, 25%–75% quartiles as upper/lower lines of boxes, 10%–90% quartiles as upper/lower vertical bars; with $n = 15$ EOMs and 56 EOMs, respectively in clusters A and B; abc letters stand for significant difference between clusters with Dunn bilateral tests.

mixed EOMs and 3 crops/residues EOMs (Table 3, See also detailed list of EOMs per clusters in SI3.2). Of the 56 EOMs from cluster B, 15 EOMs were composts, 20 were digestates and 17 were unprocessed EOMs. The cluster A grouped 15 EOMs, including 6 livestock manure EOMs composed mainly of pig manure and slurry (4 EOMs), eight urban EOMs composed of sewage sludge, and one agricultural crop/residues EOM with unspecified composition. Additional classification trees highlighted the variables explaining the affiliation of EOMs to the TE profile clusters (SI3.3 and SI3.4). According to the EOM descriptive information, the major raw material entering into the composition of EOMs was the primary discriminating factor separating EOMs composed of sewage sludge with 10 EOMs including eight in the cluster A with greater TE concentrations, from the other EOMs. Considering the TE concentrations, Cu concentration was the first factor driving cluster affiliation, separating 57 EOMs with Cu concentration below 172.9 mg/kg DM which represented all the EOMs from the cluster B from 14 EOMs with Cu concentration above 172.9 mg/kg DM including the 14 of the 15 EOMs gathered in the cluster A.

Since the 1990s–2010s, implementation of national and European environmental regulations resulted in general quality improvement of EOMs recycled in agriculture (Lopez-Rayo et al. 2016; Michaud et al. 2021; Michaud, Van Der Smissen, et al. 2025). Despite the EOM origin, the TE concentrations in the EOMs from the cluster B were below the European thresholds established for organic fertilizers and soil amendments in European regulation (EU 2019) (Figure 5) except for six EOMs for Cd, Hg, Ni, or Pb (i.e., an urban compost or digestate of residual municipal solid waste for Pb, two livestock manure EOMs for Hg, one for Ni, and one industrial digestate for Hg). For the EOMs gathered in cluster A, the concentrations of As, Cd, Hg, Ni, and Pb were below the European regulation thresholds, except for two urban EOMs composed of sewage sludge for Cd and Hg. In EOMs from cluster A, the mean and median concentrations of Cu were below the European threshold of 300 mg/kg DM; nevertheless, Cu concentration in six EOMs overpassed this threshold, including a compost of pig slurry and five urban EOMs composed of sewage sludge. Of the 15 EOMs gathered in cluster A, eight EOMs had Zn concentration overpassing the European threshold of 800 mg/kg DM, which corresponded to three EOMs composed of pig slurry

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TABLE 3 | Description of EOMs considered in the clusters of the ascending hierarchical classification based on trace elements concentrations, with the following data presented: number of EOMs per cluster (n), origin of EOMs, end-product after process, related number of EOMs (n in brackets) and associated composition (i.e., main raw materials, specification).

Cluster	Origin	End-Product after process	Composition
A ($n=15$)	Crop/residues	Composted digestate ($n=1$)	Unspecified
	Livestock manure	Compost ($n=1$)	Pig slurry
		Digestate ($n=3$)	Cattle manure, pig slurry
		Unprocessed ($n=2$)	Pig manure, pig slurry
	Urban	Compost ($n=1$)	Sewage sludge
		Dehydrated ($n=1$)	
		Digestate ($n=2$)	
		Limed ($n=1$)	
		Unprocessed ($n=3$)	
B ($n=56$)	Crop/residues	Digestate ($n=3$)	Cover crop, unspecified
	Industrial	Aerobic stabilized ($n=1$)	Agroindustrial sludge
		Digestate ($n=2$)	Unspecified
		Limed ($n=2$)	Mill sludge, agroindustrial sludge
		Unprocessed ($n=6$)	Agroindustrial plant material, agroindustrial sludge, mill sludge
	Livestock manure	Composted digestate ($n=1$)	Mix
		Compost ($n=6$)	Cattle manure, pig manure, horse manure, mix/unspecified manure
		Digestate ($n=7$)	Mix, manure, cattle slurry, pig slurry
		Unprocessed ($n=11$)	Cattle manure, goat manure, horse manure, poultry manure, sheep manure, manure, cattle slurry, poultry slurry
	Other/mixed	Compost ($n=2$)	Unspecified mix, organic amendment
		Digestate ($n=5$)	Mix, unspecified
	Urban	Compost ($n=6$)	Green waste, green waste/biowaste, residual municipal solid waste, sewage sludge, source-sorted biowaste
		Digestate ($n=3$)	Residual municipal solid waste, source-sorted biowaste
		Limed ($n=1$)	Sewage sludge

(i.e., composted, digested, or unprocessed pig slurry), two digestates of cattle manure (DM 0%–15% and 15%–25% of fresh matter), and three urban EOMs composed of sewage sludge. As observed, the EOMs overpassing the thresholds were mainly sewage sludge, which is not covered by the EU Regulation 2019/1009 (EU 2019) but is subject to limits under Directive 86/278/CEE (EU 1986), for which all EOMs were under the thresholds.

The clustering analysis highlighted that TE levels are governed by the EOM origin. Urban EOMs were found to exhibit larger TE concentrations, which is consistent with previous studies conducted on fewer EOM types (Bourdat-Deschamps et al. 2017; Munoz et al. 2021; Michaud et al. 2021). It was demonstrated that the composition of raw materials is another differentiating criterion when pig slurry and sewage sludge are the main raw materials in the EOMs, as these raw materials are potentially contaminated by TEs and, in the case of the latter, even organic contaminants (Tampio et al. 2016; Kirchmann et al. 2017; Bolan et al. 2021; Munoz et al. 2021; Levine et al. 2023). The clustering analysis also underlined that source separation of biowastes before processing, which is strongly recommended and mandatory in France, is an effective way of reducing TE levels in urban EOMs (Lopez-Rayo et al. 2016; FR 2020; Michaud, Van Der Smissen, et al. 2025).

3.4 | Applications

3.4.1 | Overview of EOM Properties

Figure 6 shows an overview of the EOMs properties considered in the present study, combining their chemical characteristics, additional C and N agronomic properties, EOM description

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Clus.	Cluster 2 (n= 18 EOMs)	Cluster 3 (n= 54 EOMs)	Cluster 1 (n= 39 EOMs)	Cluster 4 (n= 6 EOMs)
Chemical proerties.	C/N 4.1-5.4 Org. C 264-324 g/kg DM **$N-NH_4$ 35-68 g/kg DM** **N 70-114 g/kg DM** P 9-16 g/kg DM **K 48-80 g/kg DM** pH 8-8.2 Ca 26-37 g/kg DM	C/N 8.4-14.9 **Org. C 349-399 g/kg DM** $N-NH_4$ 5-17 g/kg DM N 24-51 g/kg DM P 7-16 g/kg DM K 12-34 g/kg DM pH 7.7-8.7 Ca 18-31 g/kg DM	C/N 8.2-13.7 Org. C 207-259 g/kg DM $N-NH_4$ 1-5 g/kg DM N 15-29 g/kg DM P 4-17 g/kg DM K 6-16 g/kg DM pH 7.5-8.5 Ca 34-81 g/kg DM	**C/N 17-28** Org. C 66-91 g/kg DM $N-NH_4$ 0.1 g/kg DM N 3-5 g/kg DM P 2-7 g/kg DM K 0.4-1.2 g/kg DM **Ca 298-346 g/kg DM** **pH 9.7-12.4**
CN	IROC 47-59% OM C91d. 24-37% Org. C **$N-NH_4/N$ 0.52-0.67**	IROC 58-61% OM C 91d. 21-34% Org. C $N-NH_4/N$ 0.16-0.35	**IROC 68-79% OM** **C 91d. 13-18% Org. C** $N-NH_4/N$ 0.04-0.24	not available
DM	0-15 % DM	15-50 % DM	25-75 % DM	50->75 % DM
End p.	**Digestates (67%)** Unprocessed (28%)	**Digestates (43%)** **Unprocessed (41%)**	**Composts (59%)** Unprocessed (21%)	**Unprocessed (100%)**
Origin and major raw materials	Cover crop Plant material Mix/Unspecified Unspecified Mineral concentrate Slurry *1 Mix Animal by-product Mix Unspecified Sewage sludge *1 Source-sorted biowastes	Cover crop Plant material Unspecified Plant material Sludge Vinasse Manure *3 Slurry *1 Mix Animal by-product Plant material Mix/unspecified Green waste Source-sorted biowaste Mix Sewage sludge *3	Plant material Unspecified *1 Plant material Sludge Slurry Manure Slurry *1 Animal by-product Plant material Mix/unspecified Green waste Residual municipal solid waste Source-sorted biowaste Mix Sewage sludge *4	Plant material Sludge

(Origin: agricultural crops/residues; industrial; livestock manure; mixed/other; urban)

FIGURE 6 | Overview of EOMs properties with the following data presented: the Clusters 1–4 established from the ascending hierarchical clustering based on chemical properties and organised from fertilizing to amending values (with n = number of EOMs), related chemical properties (i.e., quartiles), related C and N agronomic properties (i.e., quartiles), dry mass class (DM), major end-product after process (End p.), and main major raw material and the related origin; *number in superscript stands for the number of EOMs composed by the related major raw material exhibiting higher trace elements concentrations (i.e., pertaining to the Cluster A).

information, and risks associated with encountering EOMs with superior TE concentrations (i.e., pertaining to the TEs Cluster A), which could be seen as a framework of EOMs. EOMs belonging to all chemical Clusters 1–4 and to the Cluster B exhibiting inferior TE concentrations represent the majority of the EOMs studied here, with all origins and end-products represented. The Figure 6 emphasised that three quarters of the studied EOMs pertained to the Cluster 3 from the chemical properties clustering analysis for which intermediate properties have been found, and to the Cluster 1 which had greater potential of C storage (i.e., high IROC, low mineralized C at 91 days) and inferior NK fertilizing potential (i.e., smaller NK concentration and $N—NH_4$-to-N ratio). Those EOMs from Clusters 1 and 3, which had larger dry mass were mainly digestates, composts, and unprocessed EOMs exhibiting a huge diversity of compositions and origins, with 13 of the 15 EOMs from cluster A with larger TE concentrations (i.e., mainly composed of manure/slurry and sewage sludge). EOMs from the Cluster 2 and 4 exhibited contrasted chemical properties, with a superior NK fertilizing potential for the 18 EOMs from Cluster 2 (i.e., the largest NK concentrations and $N—NH_4$-to-N ratios), and a superior liming potential for the six EOMs from the chemical Cluster 4 (i.e., the largest pH and

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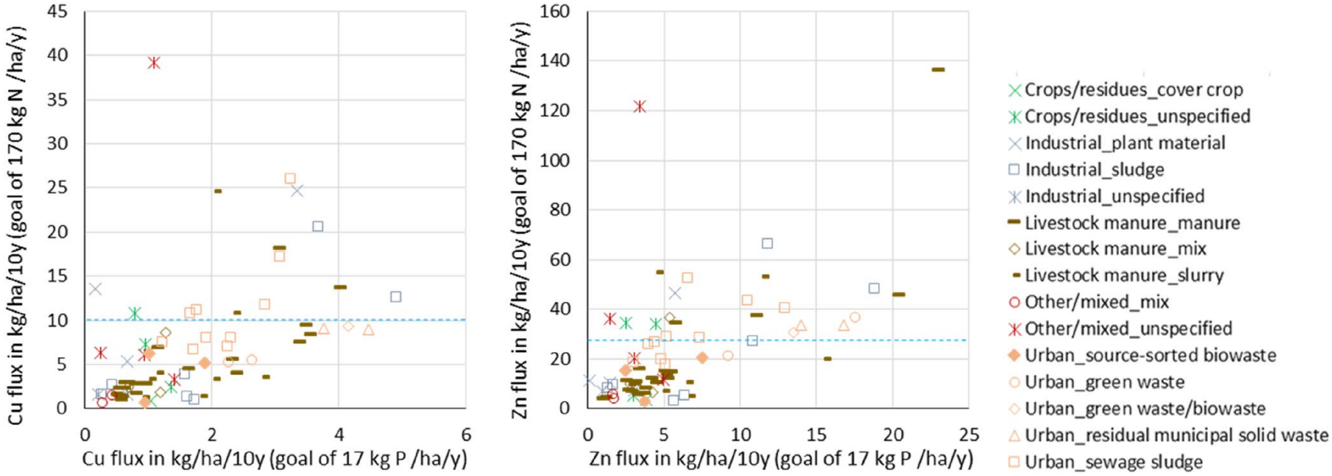

FIGURE 7 | Cumulated input fluxes over 10 years for Cu and Zn, according to the origin of EOMs and their major raw material, and expressed in kilogram per hectare, as a function of the agronomic goals of 170 kg of N per hectare every year (i.e., y-axis) and 17 kg of P per hectare every year (i.e., x-axis); French regulation (NFU 44–051/095 as blue line).

Ca concentrations). Of the EOMs from Cluster 2, which were mainly digestates and unprocessed EOMs composed of residual materials from plants/vegetables and slurry, only the unprocessed pig slurry and a digestate of sewage sludge had TE concentrations that exceeded the EU regulation (i.e., TE Cluster A).

The results underline that processing of contaminated major raw materials (i.e., pig slurry, sewage sludge) with additional raw materials could decrease the risk associated to TEs, probably by diluting the TE concentrations, such as observed with the liquid digestate of pig slurry (i.e., DM 0%–15% of fresh matter) and unprocessed pig slurry differing in their concentrations of TEs. Finally, Figure 6 summarizing the EOMs properties suggested that consideration should be given to EOMs properties prior to their application, in order to meet the plant nutrient requirements and/or to improve soil properties, and to prevent the improper use of EOMs, which can result in the over-fertilisation of nutrients and the long-term accumulation of contaminants such as TEs (Kirchmann et al. 2017; Asadu et al. 2024).

3.4.2 | Trace Element Input Fluxes in Single Agronomic Goals of EOM Applications

Regular application of EOMs to soils as organic amendments/fertilizers, even when respecting regulatory concentration thresholds, may represent a potential risk of TE soil accumulation, depending on the types and input amounts of EOMs used (Michaud et al. 2020, 2021; Kurniawati, Stankovics, et al. 2023). As a result, the maximum input fluxes of TE after 10 years of application are also included in French regulations NFU 44-051/095 (FR 2002, 2006). To verify if TE inputs to soils were within the regulated maximal thresholds, cumulated TE fluxes from repeated EOM applications (over 10 years) were estimated according to two distinct agronomic goals of EOM applications. Firstly, EOMs were used as a substitute to mineral N fertilizer (i.e., 170 kg N per hectare every year) and secondly, to substitute mineral P fertilizer (i.e., 17 kg P per hectare every year). The results show that the TE input fluxes estimated with the goal of EOMs used as a substitute to mineral N fertilizer represent the situation in which the largest amounts of EOMs are applied to meet the fertilization goal of 170 kg N per hectare (Figure 7). This results in larger input fluxes of TEs compared to the agronomic goal of 17 kg P per hectare. The cumulative input fluxes from EOMs over 10 years for As, Cd, Cr, Hg, Ni, and Pb were globally below the French regulatory thresholds, except for some EOMs (See Appendix SI4). However, it should be noted that the French regulatory thresholds were approached and even overpassed for fluxes of Cu and Zn, when considering the N fertilizing goal of 170 kg N per hectare, especially for urban EOMs composed by sewage sludge and residual municipal solid waste, industrial EOMs composed by sludge and some livestock manure EOMs (Figure 7). The calculated input fluxes agreed with the previous TE input fluxes estimated for urban composts and digestates, with greater input fluxes of Cu and Zn, particularly from the compost and digestate of sewage sludge (Tampio et al. 2016; Michaud et al. 2020). In fact, previous studies underlined risks related to Zn for which the repeated inputs of EOMs containing high levels of Zn can increase soil Zn concentration approaching toxic levels to soil microorganisms supposed to affect biological processes (Moolenaar and Beltrami 1998; Kirchmann et al. 2017; Michaud et al. 2020). To maintain safe levels of Zn in soils over a long-term period, a precautionary approach would be to limit the application amounts of EOMs containing relatively high levels of Zn, even when EU regulatory thresholds are followed (EU 2019; Michaud et al. 2020). Finally, the results suggest that repeated EOM applications should be done by mixing EOMs with different properties rather than repeating applications of EOMs with the same properties (i.e., chemical clusters, TE clusters) to avoid risks of TE contaminations as well as over-fertilisation.

3.4.3 | Input Fluxes in Practical Scenarios of EOM Applications

Usually, current farming practices involve the combined application of amending and fertilizing EOMs, especially with regard to the objectives of both replacing mineral fertilizers with organic fertilizers and maintaining or increasing soil organic C

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TABLE 4 | Practical scenarios mixing fertilizing and amending EOMs in contrasting areas and respecting the limit of 170 kg N per hectare, with: EOMs applied, corresponding amounts expressed in m^3 or t per hectare.

	"Cattle farms"		"Pig farms"		"Cereal farms"		"Peri-urban"		"Peri-urban urine"	
Year	**EOMs**	**Dose**	**EOMs**	**Dose**	**EOMs**	**Dose**	**EOMs**	**Dose**	**EOMs**	**Dose**
1	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Dig. Biow.	23.8 m^3	Unp. urine	28.8 m^3
2	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Unp. SS	26.4 m^3	Unp. urine	28.8 m^3
3	Unp. manure	20 t	Dig. slurry[a]	15 t	Unp. mill sludge	15 t	Comp. biow.	15 t	Comp. SS	15 t
	Unp. slurry	11 m^3	Dig. slurry	14.5 m^3						
4	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Dig. biow.	23.8 m^3	Unp. urine	28.8 m^3
5	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Dig. biow.	23.8 m^3	Unp. urine	28.8 m^3
6	Unp. manure	20 t	Dig. slurry[a]	15 t	Comp. SS	15 t	Comp. biow.	15 t	Comp. biow.	15 t
	Unp. slurry	11 m^3	Dig. slurry	14.5 m^3						
7	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Unp. SS	26.4 m^3	Unp. urine	28.8 m^3
8	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Dig. biow.	23.8 m^3	Unp. urine	28.8 m^3
9	Unp. manure	20 t	Dig. slurry[a]	15 t	Unp. mill sludge	15 t	Comp. SS	15 t	Comp. SS	15 t
	Unp. slurry	11 m^3	Dig. slurry	14.5 m^3						
10	Unp. slurry	26.5 m^3	Dig. slurry	26.2 m^3	Dig. cover crop	31.2 m^3	Dig. biow.	23.8 m^3	Unp. urine	28.8 m^3

Abbreviations: Biow., source-sorted biowaste; Comp., compost; Dig., digestate; SS, sewage sludge; Unp., unprocessed.
[a]Solid digestate.

concentration, contributing to improve soil fertility and health (Moinard et al. 2021; Chen et al. 2024). In order to evaluate the benefits and risks of such practices, the present study simulated the input fluxes of C, N, P, K, and TEs for five practical scenarios, including two prospective ones: cattle farms, pig farms, cereal farms (prospective), peri-urban, and peri-urban with urine (prospective) (Table 4). The scenarios considered repeated applications of local fertilizing and amending EOMs from contrasted areas. All scenarios, for which the market availability of EOMs was a limiting factor, were calculated to respect the goal of 170 kg N per hectare per year and agronomical amount and frequency of EOM application. As a result, each scenario respected the limit of 170 kg of N per hectare per year. Input fluxes of TEs respected the French regulatory thresholds, with Cu and Zn input fluxes that were far inferior to the French regulatory thresholds (FR 2002, 2006) (Table 5), even in the scenarios including EOMs composed of sewage sludge containing superior TE levels pertaining to the TE Cluster A that is, the three last scenarios (Table 4). The input fluxes of C varied from 7673 kg C per hectare per 10 years to 15,749 kg C per hectare per 10 years, and decreased as follows: "cattle farms" > "peri-urban" > "pig farms" ≈ "cereal farms" ≈ "peri-urban urine". In fact, the cattle manure EOM used to estimate the input fluxes in the "cattle farms" scenario contributed to 9.8 tons of organic carbon inputs and had an IROC index of 0.59. In cattle farm areas, this indicates that 5.8 tons from the cattle manure EOM would integrate the organic pool of soil C (i.e., three inputs with 20 tons of fresh matter per 10 years) (Lashermes et al. 2009), confirming the value of cattle farms in maintaining soil C concentrations and stocks as mentioned in previous studies (FR 2016; Launay et al. 2021; Michaud et al. 2021; Keel et al. 2025). These areas were followed by peri-urban and cereal farm areas in which regular applications of composts and digestates of source-sorted biowastes and sewage sludge would improve and/or maintain soil organic C as the "amending" EOMs considered in those scenarios pertained to the Cluster 1 from the AHC based on chemical properties (Figures 2 and 6), which exhibited significantly greater potential of organic carbon storage represented by the IROC index (Figure 3). This suggests that the soil stock of organic C would be maintained even in scenarios deprived of livestock farming,

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TABLE 5 | Cumulated input fluxes of elements estimated from the practical scenarios, expressed in kilogram per hectare per 10 years, and compared to inputs fluxes from commercial organic NP fertilizer (Org. fertilizer) and to French regulation (NFU 44-051/095).

Element	"Cattle farms"	"Pig farms"	"Cereal farms"	"Peri-urban"	"Peri-urban urine"	Org. fertilizer 170 kg N[a]	Org. fertilizer 17 kg P[a]	NFU 44-051/095
C	15,749	7997	8206	10,228	7673	9402	3303	—
N	1626	1665	1444	1672	1634	1697	596	—
P	225	350	226	377	317	482	169	—
K	2134	1047	837	758	606	383	134	—
As	0.02	0.03	0.05	0.26	na	0.01	0.00	0.9
Cd	0.02	0.01	0.02	0.03	na	0.00	0.00	0.15
Cr	0.45	0.35	0.40	1.35	na	0.18	0.06	6
Cu	2.26	3.23	2.81	4.91	na	0.79	0.28	10
Hg	0.00	0.00	0.01	0.01	na	0.00	0.00	0.1
Ni	0.47	0.34	0.38	0.87	na	0.09	0.03	3
Pb	0.54	0.21	0.53	1.73	na	0.04	0.01	9
Zn	7.83	16.27	6.89	17.96	na	6.09	2.14	30

[a]Data calculated from Michaud et al. (2020).

confirming the interest of recycling urban composts in local agricultural settings (Houot et al. 2014; Obriot et al. 2016; Noirot-Cosson et al. 2016; Michaud et al. 2021; Moinard et al. 2021). The input fluxes of P were in the same order of magnitude in all practical scenarios, with larger P inputs in "pig farms" and "peri-urban" scenarios. The input fluxes of K varied from 606 kg K per hectare in the peri-urban prospective scenario with urine to 2 134 kg K per hectare per 10 years in the scenario with cattle farms, which resulted from larger levels of K in livestock manure-based EOMs than in other EOMs (Houot et al. 2014; Caradec et al. 2025; Michaud, Van Der Smissen, et al. 2025). Input fluxes of N and P from EOM applications were in the same order of magnitude as the input fluxes calculated from a commercial NP organic fertilizer (Michaud et al. 2020). In all scenarios, N, P, and K input fluxes were in the same order of magnitude as published data of N, P, and K crop requirements for wheat, silage maize, rapeseed, and sugar beet, which represent the two main cereals, the main oilseed crop, and one of the most important production volumes encountered in European countries (Denoroy et al. 2019; EU 2023; Perez-Mercado et al. 2024). This suggests that the application of EOMs in sufficient agronomic amounts and frequency, with complementary fertilizing and amending values, would meet the plant requirements without leading to excessive NPK inputs. Nevertheless, only a part of the applied elements is available for crop uptake. Thus, the approach proposed in the present study should be completed to evaluate the field efficiency of EOM recycling in situ with the evaluation of field losses, especially for ammonia and the actual plant uptakes after the repeated EOM inputs.

Our results agreed with the suggestion of Chen et al. (2024) that is, the substitution of mineral fertilizers to meet crop demands would require more frequent application of EOMs than amending them every 2 years and/or use of EOMs with high N availability like EOMs with high fertilizing values (i.e., chemical Cluster 2). The present results confirmed the interest of using urine as fertilizer, notably in the surrounding areas of large cities, which produce huge amounts of urine, such as the Paris Basin (Martin et al. 2023). In addition, the present results show that, even in areas without livestock farms, the application of EOMs with complementary properties results in input fluxes of C, N, P, K and TEs that are equivalent to those estimated in situations that include both pig and cattle farms, as well as commercial organic NP fertilizers. When EOMs containing superior levels of TEs (i.e., EOMs composed of sewage sludge) were applied at low frequency over 10 years in alternation with EOMs containing smaller levels of TEs, such as EOMs composed notably of source-sorted biowastes, the input fluxes of C, macronutrients (i.e., N, P and K) and TEs (i.e., As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) remained at the same order of magnitude as in the "clean" situations that is, excluding EOMs containing greater levels of TEs such as in the "cattle farms" scenario. Finally, the input fluxes of elements in the prospective scenarios of "cereal farms" and "peri-urban urine" from areas without livestock farms and including digestates of cover crops and urine, respectively, were in the same order of magnitude as those calculated in the other scenarios, especially those including livestock manure EOMs.

4 | Conclusions

This study classified a wide diversity of EOMs recycled across various EU countries according to their main chemical and trace element concentrations. The clustering approach, combining Principal Component Analysis and Hierarchical Clustering, revealed consistent chemical properties patterns among EOMs driven by their origin, dry-matter class, and processing type. This multivariate typology captures the overall chemical signature of EOMs and distinguishes coherent groups along a gradient from fertilizing to amending or liming materials. It thus

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provides a robust framework for comparing EOMs and guiding their efficient and safe recycling. Practical scenarios combining amending and fertilizing EOMs demonstrated that agronomic spreading strategies mixing complementary materials result in nutrient and trace element inputs comparable to those from commercial organic fertilizers, without exceeding French regulatory thresholds, even in areas without livestock production. Further developments should aim to expand the diversity of EOMs and their characterization through additional agronomic indicators (e.g., IROC, ammonia volatilization, liming potential index) and emerging contaminants. This could include, for instance, biochars to enhance soil carbon storage while ensuring safety with respect to microplastics and per- and polyfluoroalkyl substances. Altogether, the present typology and scenarios offer a useful reference for farmers, advisors, and policymakers to improve the efficiency and safety of EOM recycling, and to design future strategies that align nutrient circularity with soil health goals.

Author Contributions

Aurélia Marcelline Michaud: conceptualization, investigation, funding acquisition, writing – original draft, methodology, validation, visualization, formal analysis, project administration, data curation, supervision. **Lucille Caradec:** conceptualization, investigation, writing – review and editing, methodology, formal analysis, software, data curation. **Elina Tampio:** conceptualization, investigation, writing – review and editing, validation. **Johanna Laakso:** conceptualization, investigation, validation, writing – review and editing. **Julie Jimenez:** conceptualization, investigation, validation, writing – review and editing, methodology. **Sabine Houot:** validation, writing – review and editing, funding acquisition, project administration.

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Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.13969793.

References

AFNOR. 2002. *French Regulation Established by AFNOR for Organic Amendments—Composts Containing Sewage Sludges. NFU 44-095*. AFNOR.

AFNOR. 2006. *French Regulation Established by AFNOR for Organic Amendments. NFU 44-051*. AFNOR.

Alloway, B., and A. Jackson. 1991. "The Behavior of Heavy-Metals in Sewage Sludge-Amended Soils." *Science of the Total Environment* 100: 151–176.

Alvarenga, P., P. Palma, C. Mourinha, et al. 2017. "Recycling Organic Wastes to Agricultural Land as a Way to Improve Its Quality: A Field Study to Evaluate Benefits and Risks." *Waste Management* 61: 582–592.

Asadu, C. O., C. A. Ezema, B. N. Ekwueme, et al. 2024. "Enhanced Efficiency Fertilizers: Overview of Production Methods, Materials Used, Nutrients Release Mechanisms, Benefits and Considerations." *Environmental Pollution and Management* 1: 32–48.

BE. 1995. Arrêté du Gouvernement Wallon Portant Réglementation de l'Utilisation sur ou dans les sols des boues d'Epuration ou de Boues Issues de Centres de Traitement de Gadoues de Fosses Septiques. Accessed June 2025. https://www.protecteau.be/sites/default/files/uploads/L%C3%A9gislations/AGW_bouesSTEP.pdf.

Bolan, N., B. Sarkar, M. Vithanage, et al. 2021. "Distribution, Behaviour, Bioavailability and Remediation of Poly- and Per-Fluoroalkyl Substances (PFAS) in Solid Biowastes and Biowaste-Treated Soil." *Environment International* 155: 1–21.

Bourdat-Deschamps, M., S. Ferhi, N. Bernet, et al. 2017. "Fate and Impacts of Pharmaceuticals and Personal Care Products After Repeated Applications of Organic Waste Products in Longterm Field Experiments." *Science of the Total Environment* 607: 271–280.

Caradec, L., A. Michaud, M. Moreira, et al. 2025. "Comprehensive Dataset on the Physicochemical Characteristics of Agrowastes Digestates From Anaerobic Digestion." *Data in Brief* 60: 111550.

Chen, H., F. Levavasseur, and S. Houot. 2024. "Substitution of Mineral N Fertilizers With Organic Wastes in Two Long-Term Field Experiments: Dynamics and Drivers of Crop Yields." *Soil Use and Management* 40: 2–12.

Chojnacka, K., K. Mikula, D. Skrzypczak, et al. 2024. "Practical Aspects of Biowastes Conversion to Fertilizers." *Biomass Conversion and Biorefinery* 14: 1515–1533. https://doi.org/10.1007/s13399-022-02477-2.

Denoroy, P., L. Jordan-Meille, and S. Sagot. 2019. COMIFER «La fertilisation P–K–Mg». Accessed June 2025. https://comifer.asso.fr/wp-content/uploads/2015/03/COMIFER_RAPPORT_fertilisation_15102019.pdf.

EU. 1986. *Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge Is Used in Agriculture*. Vol. 181, 6–12. OJ L.

EU. 1991. *Council Directive 91/676/EEC of 12 December 1991 Concerning the Protection of Waters Against Pollution Caused by Nitrates From Agricultural Sources*. Vol. 375, 1–8. OJ L.

EU. 2019. EU Law and Publications. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation (EC) No 2003/2003; UE 2019/1009; EU Law and Publications: Luxembourg, 2019. http://data.europa.eu/eli/reg/2019/1009/oj.

EU. 2023. Eurostat, Agricultural Production—Crops. Accessed June 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_crops.

EU. 2024. Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law)—General approach. Accessed June 2025. https://data.consilium.europa.eu/doc/document/ST-11299-2024-INIT/en/pdf.

FAO. 2023. *Soils, Where Food Begins: How Can Soils Continue to Sustain the Growing Need for Food Production in the Current Fertilizer Crisis?* 8. FAO.

FAO. 2025. Management and Natural Processes affecting the Biological and Chemical Aspects of Soils. Accessed October 2025. https://www.fao.org/soils-portal/soil-degradation-restoration/global-soil-health-indicators-and-assessment/soil-heath-biological-and-chemical/en/.

Fernández-Domínguez, D., D. Patureau, S. Houot, N. Sertillanges, B. Zennaro, and J. Jimenez. 2021. "Prediction of Organic Matter Accessibility and Complexity in Anaerobic Digestates." *Waste Management* 136: 132–142. https://doi.org/10.1016/j.wasman.2021.10.004.

French Ministry of Agriculture. 2016. Presentation of the "4 per 1000" Initiative-2015—French Ministry of Agriculture. Accessed June

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2025. https://4p1000.org/french-ministry-of-agriculture-2016-presentation-video/.

Glasson-Cicognani, M., and A. Berchtold. 2010. Imputation des Données Manquantes: Comparaison de Différentes Approches. 42èmes Journées de Statistique. Accessed December 2025. https://inria.hal.science/inria-00494698v1.

Grüter, R., B. Costerousse, J. Mayer, et al. 2019. "Long-Term Organic Matter Application Reduces Cadmium but Not Zinc Concentrations in Wheat." *Science of the Total Environment* 669: 608–620.

Guilayn, F., J. Jimenez, J.-L. Martel, M. Rouez, M. Crest, and D. Patureau. 2019. "First Fertilizing-Value Typology of Digestates: A Decision-Making Tool for Regulation." *Waste Management* 86: 67–79. https://doi.org/10.1016/j.wasman.2019.01.032.

Hijbeek, R., A. A. Pronk, M. K. van Ittersum, et al. 2019. "Use of Organic Inputs by Arable Farmers in Six Agro-Ecological Zones Across Europe: Drivers and Barriers." *Agriculture, Ecosystems & Environment* 275: 42–53. https://doi.org/10.1016/j.agee.2019.01.008.

Houot, S., M. N. Pons, M. Pradel, M. A. Caillaud, I. Savini, and A. Tibi. 2014. Valorisation des mati'eres fertilisantes d'origine r'esiduaire sur les sols à usage agricole ou forestier. Impacts agronomiques, (environnementaux, socio-´economiques. Expertise scientifique collective, Inra-CNRS-Irstea (France)).

Kabata-Pendians, A. 2012. *Trace Elements in Soils and Plant*. 4th ed. CRC Press Taylor & Francis Group.

Kacprzak, M., I. Kupich, A. Jasinska, and K. Fijalkowski. 2022. "Bio-Based Waste' Substrates for Degraded Soil Improvement—Advantages and Challenges in European Context." *Energies* 15: 385. https://doi.org/10.3390/en15010385.

Keel, S., A. Budai, L. Elsgaard, et al. 2025. "Efficiency of Plant Biomass Processing Pathways for Long-Term Soil Carbon Storage." *European Journal of Soil Science* 76.

Kirchmann, H., G. Borjesson, T. Katterer, and Y. Cohen. 2017. "From Agricultural Use of Sewage Sludge to Nutrient Extraction: A Soil Science Outlook." *Ambio* 46: 143–154.

Kirkby, E., and V. Römheld. 2004. *Micronutrients in Plant Physiology: Functions, Uptake and Mobility*. Vol. 543, 4–51. International Fertilizer Society.

Kopittke, P., N. Menzies, P. Wang, B. McKenna, and E. Lombi. 2019. "Soil and the Intensification of Agriculture for Global Food Security." *Environment International* 132: 1–8.

Kupper, T., D. Bürge, H. J. Bachmann, S. Güsewell, and J. Mayer. 2014. "Trace Elements in Source-Separated Compost and Digestates." *Waste Management* 34: 867–874. https://doi.org/10.1016/j.wasman.2014.02.007.

Kurniawati, A., P. Stankovics, Y. S. Hilmi, G. Toth, M. Smol, and Z. Toth. 2023. "Understanding the Future of Bio-Based Fertilisers: The EU'S Policy and Implementation." *Sustainable Chemistry for Climate Action* 3: 100033. https://doi.org/10.1016/j.scca.2023.100033.

Kurniawati, A., G. Toth, K. Ylivainio, and Z. Toth. 2023. "Opportunities and Challenges of Bio-Based Fertilizers Utilization for Improving Soil Health." *Organic Agriculture* 13: 335–350. https://doi.org/10.1007/s13165-023-00432-7.

Lashermes, G., B. Nicolardot, V. Parnaudeau, et al. 2009. "Indicator of Potential Residual Carbon in Soils After Exogenous Organic Matter Application." *European Journal of Soil Science* 60: 297–310.

Lashermes, G., B. Nicolardot, V. Parnaudeau, et al. 2010. "Typology of Exogenous Organic Materialsbased on Chemical and Biochemical Composition to Predict Potential Nitrogen Mineralization." *Bioresource Technology* 101: 157–164.

Launay, C., J. Constantin, F. Chlebowski, et al. 2021. "Estimating the Carbon Storage Potential and Greenhouse Gas Emissions of French Arable Cropland Using High-Resolution Modelling." *Global Change Biology* 27: 1645–1661.

Légifrance. 2020. LOI n°2020–105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire, JORF n°0035 du 11 février 2020.

Levavasseur, F., G. Lashermes, B. Mary, et al. 2022. "Quantifying and Simulating Carbon and Nitrogen Mineralization From Diverse Exogenous Organic Matters." *Soil Use and Management* 38: 411–425.

Levavasseur, F., B. Mary, B. Christensen, et al. 2020. "The Simple AMG Model Accurately Simulates Organic Carbon Storage in Soils After Repeated Application of Exogenous Organic Matter." *Nutrient Cycling in Agroecosystems* 117: 215–229.

Levine, A., E. Bean, F. Hinz, P. Wilson, and A. Reisinger. 2023. "Leaching of Select per-/Poly-Fluoroalkyl Substances, Pharmaceuticals, and Hormones Through Soils Amended With Composted Biosolids." *Journal of Environmental Management* 343: 1–10.

Lopez-Rayo, S., K. H. Laursen, J. D. S. Lekfeldt, F. D. Grazie, and J. Magid. 2016. "Long-Term Amendment of Urban and Animal Wastes Equivalent to More Than 100 Years of Application Had Minimal Effect on Plant Uptake of Potentially Toxic Elements." *Agriculture Ecosystems & Environment* 231: 44–53.

Martin, T., J. Aubin, E. Gilles, et al. 2023. "Comparative Study of Environmental Impacts Related to Wheat Production With Human-Urine Based Fertilizers Versus Mineral Fertilizers." *Journal of Cleaner Production* 382: 1–13.

Martinez-Ballesta, M., R. Dominguez-Perles, D. Moreno, et al. 2010. "Minerals in Plant Food: Effect of Agricultural Practices and Role in Human Health. A Review." *Agronomy for Sustainable Development* 30: 295–309.

McGrath, S. P., A. M. Chaudri, and K. E. Giller. 1995. "Long-Term Effects of Metals in Sewage-Sludge on Soils, Microorganisms and Plants." *Journal of Industrial Microbiology and Biotechnology* 14: 94–104.

Michaud, A., V. Sappin-Didier, P. Cambier, et al. 2021. "Phytoavailability of cd, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Tl and Zn in Arable Crop Systems Amended for 13 to 15 Years With Organic Waste Products." *Agronomy* 11: 664.

Michaud, A. M., M. N. Bravin, M. Galleguillos, and P. Hinsinger. 2007. "Copper Uptake and Phytotoxicity as Assessed in Situ for Durum Wheat (*Triticum turgidum* Durum L.) Cultivated in cu-Contaminated, Former Vineyard Soils." *Plant and Soil* 298: 99–111.

Michaud, A. M., P. Cambier, V. Sappin-Didier, et al. 2020. "Mass Balance and Long-Term Soil Accumulation of Trace Elements in Arable Crop Systems Amended With Urban Composts or Cattle Manure During 17 Years." *Environmental Science and Pollution Research* 27: 5367–5386.

Michaud, A. M., T. Dunsin Saliu, G. Munoz, et al. 2025. "In Situ Occurrence and Mobility of per and Polyfluoroalkyl Substances in Soils Amended With Organic Waste Products." *Science of the Total Environment* 984: 179708.

Michaud, A. M., H. Van Der Smissen, L. Caradec, et al. 2025. "Dataset on Physico-Chemical Characteristics of Exogenous Organic Materials(EOMs) Gathered From Various European Countries." *Data in Brief* 60: 111585.

Moinard, V., F. Levavasseur, and S. Houot. 2021. "Current and Potential Recycling of Exogenous Organic Matter as Fertilizers and Amendments in a French Peri-Urban Territory." *Resources, Conservation and Recycling* 169: 105523.

Moolenaar, S. W., and P. Beltrami. 1998. "Heavy Metal Balances of an Italian Soil as Affected by Sewage Sludge and Bordeaux Mixture Applications." *Journal of Environmental Quality* 27: 828–835.

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Moreno-Jiménez, E., J. Fernández, M. Puschenreiter, P. Williams, and C. Plaza. 2016. "Availability and Transfer to Grain of as, cd, cu, Ni, Pb and Zn in a Barley Agri-System: Impact of Biochar, Organic and Mineral Fertilizers." *Agriculture Ecosystems & Environment* 219: 171–178.

Morvan, T., B. Nicolardot, and L. Péan. 2006. "Biochemical Composition and Kinetics of C and N Mineralization of Animal Wastes: A Typological Approach." *Biology and Fertility of Soils* 42: 513–522.

Munoz, G., A. M. Michaud, M. Liu, et al. 2021. "Target and Nontarget Screening of PFAS in Biosolids, Composts and Other Organic Waste Products for Land Application in France." *Environmental Science & Technology* 56: 6056–6068.

Noirot-Cosson, P. E., E. Vaudour, J. M. Gilliot, B. Gabrielle, and S. Houot. 2016. "Modelling the Long-Term Effect of Urban Waste Compost Applications on Carbon and Nitrogen Dynamics in Temperate Cropland." *Soil Biology and Biochemistry* 94: 138–153.

Obriot, F., M. Stauffer, Y. Goubard, et al. 2016. "Multi-Criteria Indices to Evaluate the Effects of Repeated Organic Amendment Applications on Soil and Crop Quality." *Agriculture, Ecosystems and Environment* 232: 165–178.

O'Connor, J., B. S. Mickan, J. Rinklebe, et al. 2022. "Environmental Implications, Potential Value, and Future of Food-Waste Anaerobic Digestate Management: A Review." *Journal of Environmental Management* 318: 115519. https://doi.org/10.1016/j.jenvman.2022.115519.

Parnaudeau, V., and M. Dignac. 2007. "The Organic Matter Composition of Various Wastewater Sludges and Their Neutral Detergent Fractions as Revealed by Pyrolysis-GC/MS." *Journal of Analytical and Applied Pyrolysis* 78: 140–152.

Parnaudeau, V., B. Nicolardot, P. Robert, G. Alavoine, J. Pagès, and F. Duchiron. 2006. "Organic Matter Characteristics of Food Processing Industry Wastewaters Affecting Their C and N Mineralization in Soil Incubation." *Bioresource Technology* 97: 1284–1295.

Peltre, C., L. Thuriès, B. Barthès, et al. 2011. "Near Infrared Reflectance Spectroscopy: A Tool to Characterize the Composition of Different Types of Exogenous Organic Matter and Their Behaviour in Soil." *Soil Biology & Biochemistry* 43: 197–205.

Perez-Mercado, L., P. Simha, A. Moreira, P. Paulo, and B. Vinnerås. 2024. "Circular Fertilisers Combining Dehydrated Human Urine and Organic Wastes Can Fulfil the Macronutrient Demand of 15 Major Crops." *Science of the Total Environment* 951: 1–10.

Saliu, T., M. Liu, E. Habimana, J. Fontaine, Q. Dinh, and S. Sauvé. 2024. "PFAS Profiles in Biosolids, Composts, and Chemical Fertilizers Intended for Agricultural Land Application in Quebec (Canada)." *Journal of Hazardous Materials* 480: 1–13.

Sharma, B., A. Sarkar, P. Singh, and R. P. Singh. 2017. "Agricultural Utilization of Biosolids: A Review on Potential Effects on Soil and Plant Grown." *Waste Management* 64: 117–132.

Sterckeman, T., L. Gossiaux, S. Guimont, C. Sirguey, and Z. B. Lin. 2018. "Cadmium Mass Balance in French Soils Under Annual Crops: Scenarios for the Next Century." *Science of the Total Environment* 639: 1440–1452.

Tampio, E., F. Pettersson, S. Rasi, and M. Tuomaala. 2022. "Application of Mathematical Optimization to Exploit Regional Nutrient Recycling Potential of Biogas Plant Digestate." *Waste Management* 149: 105–113.

Tampio, E., T. Salo, and J. Rintala. 2016. "Agronomic Characteristics of Five Different Urban Waste Digestates." *Journal of Environmental Management* 169: 293–302.

Tian, K., Z. Xing, G. Liu, et al. 2018. "Cadmium Phytoavailability Under Greenhouse Vegetable Production System Measured by difAlvarenga Et al. 2017fusive Gradients in Thin Films (DGT) and Its Implications for the Soil Threshold." *Environmental Pollution* 241: 412–421.

Viala, Y., J. Laurette, L. Denaix, et al. 2017. "Predictive Statistical Modelling of Cadmium Content in Durum Wheat Grain Based on Soil Parameters." *Environmental Science and Pollution Research* 24: 20641–20654.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** Supporting Information.

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