Løes *et al. Environmental Sciences Europe* (2024) 36:199
https://doi.org/10.1186/s12302-024-01016-2

Environmental Sciences Europe

RESEARCH

Open Access

Calculating the effect of intensive use of urban organic waste on soil concentrations of potentially toxic elements in a peri-urban agriculture context in Norway

Anne-Kristin Løes[1*], Sebastian Eiter[2*] and Tatiana Rittl[1]

Abstract

Background Recycling nutrients and organic matter available as waste in urban areas may close nutrient gaps and improve soil quality, but the concentrations of potentially toxic elements (PTEs) are commonly higher than in mineral fertilisers. How quickly may the limits for soil quality be exceeded, and for which elements, if such materials are applied intensively? For a rough answer to this question, we used soil data from ten case farms near Oslo and Bergen (Norway) to estimate how PTE concentrations increased when the demand for nitrogen (N), phosphorus (P) and potassium (K) in a theoretical carrot crop produced every year was covered by compost or digestate from source-separated food waste, or composted garden waste, compared with manure from horses and poultry which are often kept in peri-urban areas.

Results With the intensive fertilisation assumed here, the Norwegian soil quality limits for PTEs were reached within 20–85 years, and faster for soil with more organic matter since regulatory limits set by weight discriminate soils with low bulk density. The limits were reached first for Cu and Zn, which are both essential micronutrients for crop plants. The concentrations of macronutrients in the urban waste-based fertilisers were not well balanced. Rates covering the K demand would lead to high surpluses of P and N. In peri-urban vegetable growing, high applications of compost are not unusual, but more balanced fertilisation is required.

Conclusions The Norwegian regulations for PTEs in organic soil amendments and agricultural soil are stricter than in the EU, and do not support recycling of organic matter and nutrients from urban waste. Many materials which can only be applied with restricted amounts to Norwegian agricultural soil, may be applied according to crop demand in the EU. Growers utilising urban waste-based fertilisers intensively should monitor the soil regularly, including PTE analyses. Soil sampling should occur on fixed sampling points to reveal changes in concentrations over time. Norwegian authorities should consider a revision of the organic fertiliser regulation to support recycling of valuable organic materials. There is a need for more data on the PTE concentrations in agricultural soil and organic fertiliser materials.

Keywords Cadmium, Copper, Zinc, Small-scale vegetable growing, Food wastes, Urban agriculture, Compost, Digestate

*Correspondence:
Anne-Kristin Løes
anne-kristin.loes@norsok.no
Sebastian Eiter
sebastian.eiter@nibio.no

Springer Open

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Background

Urban agriculture is recognised in the EU biodiversity strategy as an important tool for urban and peri-urban greening, and to stop the loss of biodiversity in cities [8]. Urban growers commonly apply direct sales of products, and there is a high interest in "market gardens" where vegetables are grown for direct sale, usually with fixed growing beds, manual management, and purchase of fertilisers. To reduce the carbon footprint of such growing systems, locally available organic materials should be recycled as fertilisers [14]. In urban areas, the soil may be polluted by emissions from traffic, former industrial activities, construction work and more [31]. Hence, when new growing sites are established the risk of soil pollution should be considered. An important soil function in urban areas is the handling of organic waste, such as from gardens and food residues. When organic wastes are used for soil amendment, organic matter is decomposed, and nutrients recycled. Large volumes of nutrients and organic matter are brought into urban areas with human consumption, and it is of interest to study how peri-urban areas may become self-sufficient in plant nutrients and organic matter for maintenance of soil health and fertility. Fertilisers and soil amendment products derived from urban food consumption are currently not much utilised in Norwegian market gardens. A survey conducted in 2020 [16] revealed that only 23% of the growers applied "purchased compost", but this may not necessarily be derived from urban waste. More common was the on-site application of compost made from locally available substrates. Most growers had access to animal manure from nearby farms. Application of commercial, pelleted poultry manure was also very common, and almost all growers used mulch from grass mowing or other decomposing material to apply nutrients and reduce the need for weeding. Green manure was also common, whereas only 14% of the growers applied mineral fertilisers.

For organic soil amendments, it is especially toxic ("heavy") metals that are regulated as potentially toxic elements (PTEs). These elements are toxic above certain thresholds and should thus not accumulate above critical levels in the soil. The EU fertiliser regulation (EC 2019) has limits for inorganic arsenic (As), cadmium (Cd), chromium (CrVI), copper (Cu), mercury (Hg), lead (Pb), nickel (Ni) and zinc (Zn) in organic and organo-mineral fertilisers. Norwegian regulations on organic fertilisers [12] and soil pollution [13] have limits for the same metals, but the limits and some other details differ from EU regulations, as will be discussed in this paper. As shown by a comprehensive assessment of PTEs in the various organic fertiliser materials in Germany [18], the concentration of Cd, assessed per kg of phosphorus (P), may be significant. For example, as an average value for 1061 samples, composted green waste had 184 mg Cd per kg of P. This is well above values presented by the Norwegian Scientific Committee for Food and Environment [28], Table AVI-2, p. 386), where the content of Cd per kg of P varied from 27 to 85 mg for various mineral fertilisers commonly applied in Norway. The highest level of PTEs in two types of mineral fertilisers was found for Zn, about 1500 mg per kg P [18, 28], the amount of Zn per kg P was 70 000 mg (=70 g) Zn per kg P. Hence, intensive application of such materials may increase soil concentrations of PTEs. The concentrations of PTEs in soil depend on several factors. Inputs, such as fertilisers, liming and other soil amendments may not always be the most important [29]. Geology and local pollution lead to significant variations, and leaching and runoff varies with precipitation, soil type (texture, pH, soil organic matter), type of PTE and other conditions. PTEs are also taken up by crop plants. Whereas all these factors can only be taken into considerations in extensive reports, such as the comprehensive risk assessment of PTEs in theNorwegian food chain [28], it may still be of interest to conduct a simple investigation of the fate of PTEs with intensive application of various organic fertiliser materials. Many countries are not self-sufficient in plant nutrients, and crop production may possibly have to rely on recycling of nutrients and organic matter to a much larger extent in the future. This is also well in line with public policy both in Norway and Europe.

The aim of the current paper is to study if Norwegian limits of PTEs in organic fertilisers are reasonable when compared with other national regulations, and if they foster or hamper a recycling of organic matter and nutrients in a peri-urban context where utilisation of local organic waste should be maximised. To assess this, we estimated how much the soil PTE concentrations may increase by intensive application of urban organic waste, and how fast the current soil quality limits may be exceeded, using ten case farms near Oslo or Bergen as a baseline for current soil PTE concentrations. The farms had a direct sales business model and would welcome increased utilisation of urban waste-based fertilisers.

Methods

Assumptions and context

To assess in a simple way how the concentrations of PTEs in a soil may be affected by an intensive application of urban organic waste, and how fast the current soil quality limits may be exceeded, we made several assumptions:

1. The soil would be used for carrots every year, with no crop rotation.

2. The demand for macronutrients nitrogen (N), phosphorus (P) and potassium (K) would be covered 100% by urban waste-based fertilisers (UWFs), even if the rates exceed current regulations.
3. For two types of animal manure applied as UWFs, the rate of manure per unit area may exceed the EU nitrate directive [9].
4. The bulk density of air-dry soil in the laboratory equals the field bulk density of dry soil.
5. All PTEs included in the UWFs would accumulate in the soil.
6. The soil bulk density would not be affected by the fertilisation practice.
7. Inherent soil characteristics (pH, organic matter, etc.) would not affect on the accumulation of PTEs in the soil.

Since these assumptions are very simplistic, we assessed the effect of subtracting the uptake of PTEs in the crop and including leaching and runoff (assumption 5).

As a baseline for current soil PTE concentrations in a peri-urban context, we applied ten case farms near Oslo or Bergen (Table 1). The farms participated in a research project (2019–2023) to study the potential of peri-urban professional farmers to utilise their geographical location for developing successful business models including direct sales. Most farmers had additional income from work outside the farm. Several farms had intensive horticultural production. The farms were relatively small, with 1–6 hectares of cultivated land. The average size of cultivated land on a Norwegian farm is 26 hectares [27]. The current fertilisation comprised a variety of animal manure, from cattle slurry to composted solid manure, commonly received from neighbour farms. Commercial poultry manure fertiliser enriched with potassium was purchased by the vegetable growers. All farmers were interested in applying more UWF if locally available at a reasonable price.

Table 1 Location (near Bergen (B) or Oslo (O)), main production for income, amount of cultivated area (ha) and current fertilisation practice on ten case farms

Farm ID	Location	Main production	ha	Current fertilisation
1	B	Meat (pork, goat), eggs	1.5	Cattle slurry
2	B	Meat (cattle)	4.7	Cattle slurry, MF
3	B	Meat (sheep), strawberries	6.3	Poultry manure, MF
4	B	Berries, fruit, tourism	1.6	Sheep manure, MF
5	B	Meat (cattle, sheep)	1.5	Manure from own farm
6	B	Vegetables, flowers	1.5	Manure, CPMF
7	O	Vegetables	1.0	Horse manure
8	O	Vegetables, eggs	2.0	Compost (HM), CPMF
9	O	Rented out for vegetables	5.6	Cattle slurry, CPMF
10	O	Vegetables	5.8	Manure from own farm

MF = mineral fertiliser, CPMF = commercial poultry manure fertiliser, HM = horse manure

Analyses of soil characteristics

The baseline of soil PTE concentrations was derived from soil analyses of samples collected in 2020 (Tables 3, 4). Cultivated topsoil (0–20 cm) was sampled at fixed points recorded with GPS coordinates. For each sampling point, six composite samples were merged for analysis of bulk density, pH (soil:water 1:5 by volume), loss on ignition (LOI), ammonium acetate-lactate (AL)-soluble P, K, calcium (Ca), magnesium (Mg), and acid-soluble K. With a standardised volume and filling procedure, the bulk density of sieved, air-dry soil has been shown to be closely correlated with field bulk density, with a somewhat lower value, 75–90% of the value measured in field for different soil types (clay, sand, silt) [25].The LOI is a measure for the content of soil organic matter. By the determination of AL-extractable nutrients, the soil is extracted with 0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75 with a ratio of soil to solution of 1:20 [6]. Acid-soluble K, as a measure of less readily plant available K, was analysed after extracting the soil with 1 M nitric acid (HNO_3). Mean values of pH were computed as the mean value of the negative log value of the H^+ concentrations. For a subset of samples from each farm, PTE concentrations were measured after extraction by aqua regia, a mixture of nitric acid and hydrochloric acid (HCl). Detection of the elements was done by inductively coupled plasma-mass spectrometry (ICP-MS). The soil analyses were conducted by Eurofins Agro Testing. Across the 10 sampled farms, 75 samples were analysed for pH, LOI, bulk density and AL-soluble nutrients, whereas 1/3 of samples were additionally analysed for PTEs. Element concentrations and other characteristics for two baseline soils, representing the Oslo and the Bergen area, were computed as the average of the average values of each farm (Table 2).

Fertiliser materials

The selected materials comprised green waste from gardens and recreational areas; source-separated organic waste (SSOW) from households, catering, and retail; horse manure; and poultry manure. Green waste is commonly treated as compost, while SSOW may be anaerobically digested, or composted. We have presented data for digested SSOW from biogas plants

Table 2 Mean values for soil characteristics for ten farms located near Bergen or Oslo, Norway

Region	*Farm (n)*	BD	pH	LOI	P-AL	K-AL	Mg–AL	Ca-AL	K-HNO_3
Bergen	*1 (7)*	0.83	4.9	37	21	7	9	54	32
Bergen	*2 (17)*	0.60	5.5	31	17	5	9	179	36
Bergen	*3 (5)*	0.84	5.8	14	20	13	21	156	221
Bergen	*4 (5)*	1.05	5.5	7	10	6	7	65	43
Bergen	*5 (11)*	0.81	6.1	22	23	8	17	395	30
Bergen	*6 (4)*	1.08	5.9	8	46	15	22	183	178
Oslo	*8 (9)*	0.90	5.9	19	11	11	17	167	38
Oslo	*9 (9)*	1.22	5.7	5	16	17	10	142	69
Oslo	*10 (3)*	1.13	5.9	7	8	14	9	160	62
Oslo	*11 (5)*	1.16	6.7	6	31	25	24	232	81
Mean, Bergen		0.87	5.4	20	23	9	14	172	90
Mean, Oslo		1.10	5.9	10	17	17	15	175	62

BD = bulk density in air-dried, sieved soil, kg dm^{-3}; LOI = loss on ignition, % of DM; AL-extractable nutrients and acid-soluble K in mg 100 g^{-1} air-dried soil. *n* = number of topsoil samples per farm

Table 3 Mean concentration values (mg kg^{-1} dry soil) of potentially toxic elements for farms located near Bergen or Oslo, Norway, with mean values compared with content per litre soil (mg dm^{-3}), and threshold values for soil quality from Norwegian regulations on organic fertilisers [12] and pollution [13]

Region	*Farm (n)*	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Bergen	*1 (1)*	5	0.6	15	47	0.05	8	36	60
Bergen	*2 (3)*	4.7	0.5	27	33	0.17	29	31	59
Bergen	*3 (4)*	< 2.0	0.7	40	35	0.07	27	19	90
Bergen	*4 (3)*	4	0.5	56	17	0.05	26	28	78
Bergen	*5 (1)*	5	0.4	14	39	0.26	6	19	53
Bergen	*6 (2)*	5.5	0.6	24	28	0.05	17	21	97
Oslo	*7 (3)*	5.7	0.5	31	18	0.09	26	18	90
Oslo	*8 (2)*	4.5	0.3	27	13	0.07	14	20	95
Oslo	*9 (1)*	4	0.6	25	9	0.04	17	16	53
Oslo	*10 (5)*	2.3	0.3	16	7	0.04	9	16	53
Mean, reg. Bergen mg kg^{-1}		*4.8*	*0.6*	*29*	*33*	*0.11*	*19*	*26*	*73*
Mean, reg. Oslo mg kg^{-1}		*4.1*	*0.4*	*25*	*12*	*0.06*	*17*	*17*	*73*
Mean, reg. Bergen mg dm^{-3}		*4.2*	*0.5*	*25*	*29*	*0.10*	*17*	*23*	*64*
Mean, reg. Oslo mg dm^{-3}		*4.5*	*0.4*	*28*	*13*	*0.07*	*19*	*19*	*80*
Threshold FOR 2003 mg kg^{-1}		–	1	100	50	1	30	50	150
Threshold FOR 2004 mg kg^{-1}		8	1.5	50	100	1	60	60	200

n = number of topsoil samples per farm

where other substrates were kept to a minimum. Horses for sporting activities are common in peri-urban areas and proper utilisation of this manure is a challenge. Poultry manure is commonly applied in urban growing [16], (Table 1), and such animals may also fit well in a peri-urban context. Human waste includes significant amounts of organic matter and nutrients in sewage but was not included because fertilisers or soil amendments containing sewage sludge are not permitted for growing of vegetables in Norway [12]. An overview of the selected fertiliser materials is shown in Fig. 1.

Calculations

Carrots have a nutrient demand of 90 kg ha^{-1} for N, 30 kg ha^{-1} for P and 140 kg ha^{-1} for K, for an annual yield of 50 tons per hectare [30]. For small-scale growing, the numbers are better presented as 9 g N, 3 g P and 14 g K m^{-2}. Carrots also require micronutrients, such

Table 4 Mean values for chemical characteristics and nutrient concentrations in urban waste-based fertilisers and soil amendments from Norway (NO), compared with German reference values [18] and a Norwegian inventory for poultry manure [5]

Reference	n	pH	EC	DM%	LOI	Tot-C	Tot-N	Tot-P	Tot-K	Tot-Ca
SSOW compost										
Mean value, NO	5	8.6	1054	38	61	33	2.15	0.53	0.61	8.8
[18]	756	–	–	64	40	24	1.53	0.36	1.10	2.7
SSOW digestate										
Mean value, NO	8	8.0	2119	2.20	–	24	17	0.90	7.40	3.1
[18]	719	–	–	5.2	60	47	12.1	1.63	4.31	–
Green waste compost										
Mean value, NO	10	7.8	270	55	33	18	1.0	0.21	0.46	1.46
[18]	1061	–	–	63	37	23	1.15	0.22	0.85	3.10
Horse manure										
Composted NO	3	7.1	440	29	70	38	1.33	0.26	1.03	1.06
Fresh, [18]	2–8	–	–	31	85	–	1.86	0.39	2.99	0.76
Poultry manure										
Commercial product	2	5.6	–	90	–	40	8.07	3.57	4.28	5.86
[5]	9	–	–	60	–	–	3.76	1.62	2.06	9.86

Number of soil samples (n) per material. EC = electric conductivity, mS m^{-1}. LOI = loss on ignition. All concentrations in % of dry matter (DM)

as copper (Cu) and zinc (Zn), which are also PTEs. In a study of conventional vs. organically grown carrots in the Czech Republic [15], comprising totally 142 retail samples, the average content was 0.71 mg Cu and 6.4 mg Zn per kg of roots. This comprises 3.6 mg Cu and 32 mg Zn per m^2 as an annual output of these elements, if carrots were grown every year. The total input of PTE per m^2 of soil was calculated when the demand for N, P and K was covered with digestate from mainly SSOW, composted SSOW, composted green waste, horse manure, and poultry manure, applying PTE concentrations presented in the Results section. For all fertiliser materials, the K demand resulted in the highest demand for application (Fig. 2), and the amounts were set to cover this demand.

To compute the number of years required for the baseline soils in the Bergen and Oslo region to reach the Norwegian soil quality thresholds for PTEs [13], the average soil concentration of each element (Table 4) was subtracted from the threshold value, and the difference (= residual concentration) was considered as being available for accumulation of PTEs. For arsenic (As), 8 mg per kg dry soil was applied as threshold [13], (Table 4). Since fertilisers are applied per volume (area) of soil, not per kg, the residual concentration was transferred to volume basis by multiplying it with the weight of the topsoil layer (0–20 cm = 0.2 m) on an area of 1 m^2. The value was 1 $m^2 \times 0.2$ m $\times$ 870 kg m^{-3} = 174 kg in the Bergen region, and 1 $m^2 \times 0.2$ m $\times$ 1100 kg m^{-3} = 220 kg in the Oslo region (see Table 2 for mean values of bulk density). A correction factor between 1.13 and 1.33 is usually applied to convert (by multiplication) the bulk density of air-dry, sieved soil to field conditions [25]. We did not have precise information to do this adjustment, and hence the field bulk density is underestimated by 10–25% (see Methods). This underestimation will lead to a more rapid accumulation of PTEs in the soil.

The resulting content of each PTE per m^2 of topsoil was divided by the amount of the respective PTE contained in the maximum amount of fertiliser required to cover the carrots' demand for K. Values for PTE concentrations in fertiliser materials are found in Table 5. For As, few values were available and some relevant values from other sources are referred in connection with Table 5. Since this amount of fertiliser is given annually, the output of this calculation is a number of years, as shown for Cd in the Bergen region when SSOW compost was applied as a fertiliser, in the example below:

[(1–0.6) mg Cd $kg^{-1} \times 174$ kg m^{-2}]/(0.45 mg Cd $kg^{-1} \times 2.299$ kg DM m^{-2} y^{-1}) = 67 years.

Since this calculation is based on several assumptions that are not realistic, we also conducted a second calculation where the amount of PTEs in carrots were assumed to be the average values of organic and conventional carrots analysed by [15], and these amounts of PTEs were removed annually. These amounts comprise, per m^2 per year, 0.59 mg for As, 0.32 mg for Cd, 0.26 mg for Cr, 3.6 mg for Cu, 7.0 mg for Ni, 0.27 mg for Pb and 32 mg for Zn. For Hg, no values were presented by [15], but according to [28], plant uptake of Hg is very low and hence Hg uptake was assumed to be zero. We further assumed that leaching and runoff in combination would remove PTEs as described for the sites being

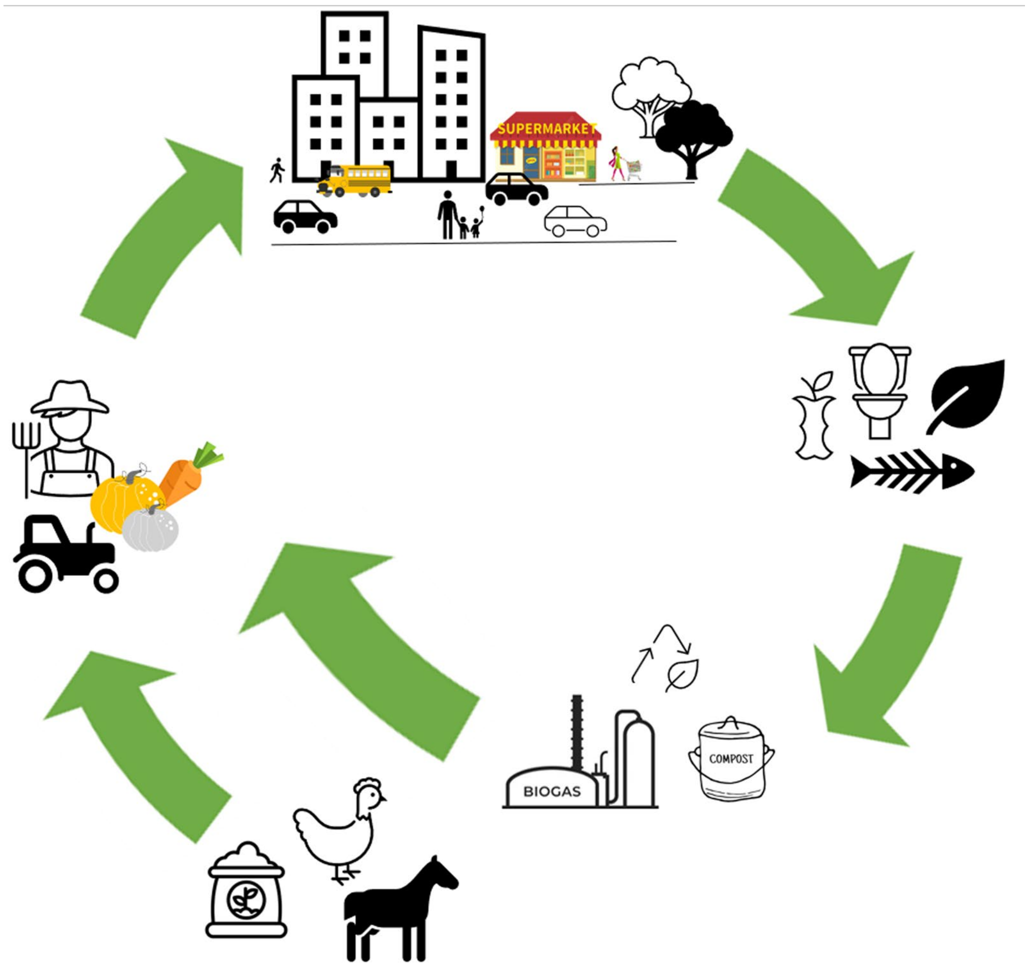

Fig. 1 Streams of organic materials from cultivated land to urban food consumers that may be recycled into urban waste-based fertilisers via composting or anaerobic digestion, complemented by selected animal manure products (horses + poultry)

most close to Oslo and Bergen in the [28] risk assessment. These sites were Ås (about 40 km SW of Oslo) and Time (about 180 km south of Bergen). The values comprise, for Ås/Time in mg per m^2 and year: 1.5/3.8 mg of As; 0.5/2.4 mg of Cd, 14.4/16.0 of Cr, 4.7/19.9 mg of Cu, 0.002/0.01 mg of Hg, 38.4/37.9 mg of Ni, 1.2/7.2 mg of Pb and 54/126 mg of Zn. The second calculation was conducted as the first, except that the sum of the respective PTE in plant uptake and leaching/runoff was subtracted from the annual input.

Chemical analyses of fertiliser materials

Chemical characteristics of the selected fertiliser materials were compiled from projects conducted by the Norwegian Institute for Bioeconomy Research (NIBIO) since 2006 (personal communication Trond Haraldsen), with analyses conducted by Eurofins. SSOW composts were provided by Agder Renovasjon and Lindum AS. The composts were made with bark as a structure material, and calcium hydroxide was applied to prevent odour. Values for SSOW digestate were provided by Hadeland and Ringerike Avfallsselskap AS (HRA, 3 samples), Mjøsanlegget AS (3 samples) and Indre Agder og Telemark Avfallsselskap IKS (IATA), 2 samples), all analysed between 2008 and 2013. Green waste compost was provided by Romerike Avfallsforedling (ROAF, Skedsmokorset, near Oslo), Norsk Miljø Industri (Larvik), and Lindum (Drammen). Composted horse manure was provided from Bjerke farm (Slependen, near Oslo), and several stables near Bergen. Commercial poultry manure enriched with mineral potassium (Grønn Øko in 2019, Grønn 8 k in 2020) was analysed by Eurofins in a former project at NORSØK.

For the characterisation of materials, electric conductivity and pH were measured in deionised water with a substrate:water ratio of 1:5. LOI was measured as described for soil analyses above. Total N was measured as Kjeldahl-N. Total C was measured by combusting

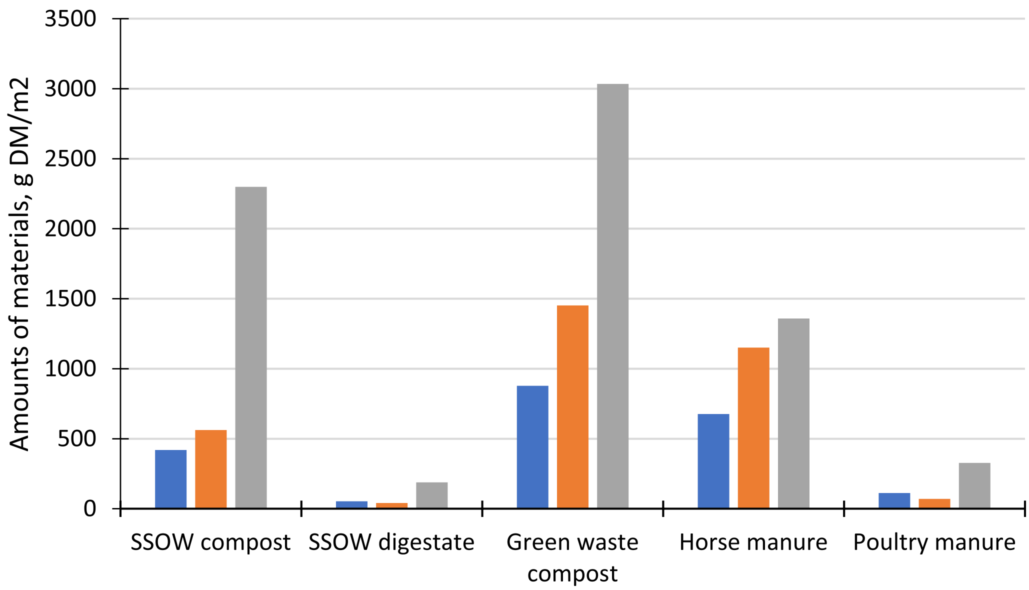

Fig. 2 Amounts of materials (kg dry matter m^{-2}) required to cover the demand for N (blue columns), P (orange columns) and K (grey columns) in a carrot crop demanding 90 kg ha^{-1} of N, 30 kg of P and 140 kg of K, corresponding to 9, 3 and 14 g m^{-2}. SSOW = source-separated organic waste from private households, catering, and retail

Table 5 Mean values of PTE concentrations in compost and digestate from source-separated organic waste (SSOW), composted garden waste, horse manure and poultry manure from Norway (NO), compared with German reference values [18] and a Norwegian inventory for poultry manure [5]

Reference	n	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Composted SSOW									
Mean value, NO	5	–	0.45*	11	38	0.06	7.7	9.1	165
[18]	756	–	0.46	28	54	0.11	19	45	213
Digestate from SSOW									
Mean value, NO	2–8	–	0.41*	6.9	46	0.03	4.3	6.2	412**
[18]	719	–	0.40	17	82	0.10	15	10	348
Composted organic waste from gardens and recreational areas									
Mean value, NO	10	–	0.45*	32	40	0.08	13	24	186*
[18]	1061	–	0.40	23	34	0.11	14	32	154
Horse manure									
Composted, NO	3	–	0.28	15	123*	0.03	9	32	123
Fresh, [18]	2–8	0.75	0.36	11	13	0.05	4	1.3	71
Poultry manure									
Commercial product	2	0.26	< 0.1	3	19	< 0.01	1.8	0.71	185*
[5]	14	0.89	0.16	2	62	–	3	1.0	343

n = number of samples. All concentrations in mg kg^{-1} dry matter (DM). For each PTE, the selected Norwegian fertiliser materials are classified with no sign for Class 0

*for Class I and

**for Class II [12]

air-dried and grinded samples and detecting the carbon via elemental analysis. Total elements (macronutrients and PTEs) were measured after extraction in aqua regia, as described for soil samples above.

The selected materials (Tables 4 and 5) were compared with values in a comprehensive review of characteristics of organic fertiliser materials from Germany [18], except for poultry manure which was compared with values from a national inventory of animal manure [5].

Regulations

The relevant regulations were reviewed and are referred in the Results section.

Results

Soil characteristics and baseline values

Soils on peri-urban farms located near Bergen had a lower bulk density and pH, significantly more organic matter, somewhat more extractable P, less extractable K but more acid-soluble K than soils on peri-urban farms near Oslo (Table 2). These results reflect that the mean annual precipitation in Bergen is significantly higher than in Oslo: 2495 mm compared with 863 mm in Oslo during 1991–2020 [11]. Wet conditions tend to increase soil organic matter.

For all PTEs except zinc (Zn), the concentrations were higher near Bergen than near Oslo (Table 3). With more soil organic matter, the soil bulk density decreases. On a volume basis, since the soils are generally lighter near Bergen, the differences between locations disappear for most elements, except copper (Cu), mercury (Hg) and lead (Pb). A somewhat higher content of Cu and Hg in the soil near Bergen may be due to higher content of soil organic matter, since these elements are bound by organic matter in the soil. Linear regressions made between PET concentrations and loss on ignition (LOI) were statistically significant ($p < 0.05$), with an r-square value of 0.32 for Cu and 0.50 for Hg. For Pb, the relationship with LOI values was not significant.

The Norwegian regulation on reduction of pollution [13], Attachment I) defines norm values of PTE concentrations in soil above which the soil is defined as polluted, and hence should not be exceeded [19]. These values are shown in Table 3, along with values defined in quality criteria for agricultural soil in the Norwegian regulation for organic fertilisers and soil amendments [12]. Soils where organic amendments with PTE concentrations above certain limits (see below) is applied, shall not exceed these limits. As shown in Table 3, the average values of the soils near Bergen and Oslo are well below the limits in both regulations.

Chemical characteristics of fertiliser materials

The selected fertiliser materials were solid, with a dry matter (DM) content of 29% or higher (by weight, Table 4), except for digestate from source-separated organic household waste (SSOW). On a dry matter basis, the SSOW compost had much more N than green waste compost, 2.15% of DM compared with 1.0. The digested SSOW had a very high N concentration, but the dry matter content in this liquid material is difficult to measure precisely and inaccuracies will have a significant effect on the concentration values (g kg^{-1} DM). Ammonium may represent a significant part of the mineral content and may get lost as ammonia (NH_3) during drying, which will affect the DM determination.

P and K concentrations were also higher in SSOW compost than green waste compost. Horse manure had lower concentrations of N and P than SSOW compost, roughly comparable with green waste compost, but the concentration of K was higher than in SSOW compost. Commercial organic fertiliser made from poultry manure and mineral potassium had much higher concentrations of all minerals than the other materials. For comparison, since the number of analyses for each material is quite low, German reference values have been cited, except from for poultry manure where Norwegian data were available. The German values are derived from a comprehensive compilation of analytical results produced by public authorities and educational institutions [18]. Since no similar data were available from any Scandinavian or Nordic country, we found Germany to be a relevant country for comparison because the waste treatment system is comparable with what is described here, and the consumption pattern is quite similar. The comparison of averages of very few values and these references must be done with care, but it could seem that K concentrations in compost are lower in Norway. This may possibly be due to less favourable storage conditions for maturing compost windrows in Norway, with more precipitation entering the windrows, as shown by a higher DM% in the German average values. The most important is to assess the concentrations of PTEs, to avoid that the Norwegian values applied in the calculations below are unrealistic. This comparison is conducted in Table 5.

For PTEs, very few values were found for arsenic (As) [27, P.95] tates an average value of 0.8 mg As kg DM for poultry manure, and 1.2 mg for horse manure. A report for the European Commission [1] states a value of 5–10 mg As kg^{-1} DM in "biowaste, compost", which is similar to SSOW compost. In our calculations, we applied a value of 7.5 mg As kg^{-1} DM for compost and digestate from SSOW and green waste compost, 0.8 mg for poultry manure and 1.2 mg for horse manure.

The Cd concentration was quite similar in the selected fertiliser materials and the German reference materials (Table 5). For other PTEs, the concentrations seemed to be higher in compost and digestate from SSOW in Germany, but quite similar in green waste compost and horse manure. For poultry manure, the commercial product (Table 5) had less PTEs than the average values in manure for laying hens. The asterisks in Table 5 refer to Norwegian regulations, explained in the next section. As can be seen, all materials are restricted with respect to the amount of application, due to the concentrations of Cd for SSOW compost, of Cd and Zn for SSOW digestate and green waste compost, of Cu for horse manure, and of Zn for the commercial poultry manure-based product.

Regulations of PTEs in soil and soil amendments

For organic fertilisers and soil amendments, Norwegian legislation sets limits for seven potentially toxic elements: cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), nickel (Ni) and zinc (Zn) (FOR 2003). Recently, limits were also proposed for arsenic (As; [20]. The threshold values for PTEs in organic fertilisers in the EU [10] are compared with Norwegian values in Table 6, along with soil quality limits. In addition to the seven elements regulated in the Norwegian regulation for fertilisers, the EU has a limit for inorganic arsenic (As). For chromium, the EU fertiliser regulation [10] puts a limit to Cr(VI), whereas the Norwegian limit is for total Cr. Whereas the EU regulation only has a maximum limit of PTE concentrations in organic fertilisers, the Norwegian legislation divides organic soil amendments and fertilisers into four quality classes 0–III [12]. Materials in class 0 may be applied according to crop nutrient demand. Materials in class I may be applied with maximum 40 Mg dry matter (DM) ha^{-1}, corresponding to 4 kg DM m^{-2}, during a period of 10 years, and materials in class II with maximum 20 Mg DM ha^{-1} over 10 years. Such materials may also be applied to land not applied for cultivation of feed or food crops, and Materials in class III may only be applied on such land (e.g. along roads and to cover waste deposits).

The threshold values for Cd, Hg and Cu concentrations in organic fertiliser in the EU are between the limits for Class I and II in the Norwegian regulation, whereas for Pb the limit is between Class II and III, and for Ni and Zn it is equal to the upper limit of Class II materials in Norway. This implies that many materials which could only be applied with restricted amounts to Norwegian agricultural soil, may be applied according to crop demand in most other European countries.

The Norwegian regulation for organic fertilisers and soil amendments [12] includes quality criteria for agricultural soil, by means of limits of PTEs where soil exceeding the limits cannot be amended with materials in quality Class I or II (Table 6, right part). The Norwegian regulation on reduction of pollution [13], Attachment I) defines norm values of PTE concentrations in soil above which the soil is defined as polluted, and hence should not be exceeded [19]. Whereas the Norwegian regulation [12] is stricter than the EU regulation [10] concerning concentrations of PTEs in organic fertilisers or soil conditioners, the soil quality limits do not differ as much.

In addition to the seven elements described in [12], the national regulation on pollution [13] sets limits for concentrations of As in soil. For soil concentrations of Cd, Cu and Zn, [13] has significantly higher limits than [12], whereas for Cr, [13] is less strict than [12]. The Norwegian soil limit values are in the lower part of the EU range for soil guideline values (Table 6), and also of the sewage sludge directive [7]. However, this limit was set

Table 6 Left part (Soil amendment limits): upper limits of concentrations of potentially toxic elements (PTEs, mg kg^{-1} dry matter) allowed in organic fertilisers in the EU [10] and in soil amendments and organic fertilisers of quality Classes 0–III in Norway [12]. Right part (Soil quality limits): limits of PTE concentrations in Norwegian agricultural soil where materials in Class I or II shall be applied [12]; limits given in the regulation on restriction of pollution [13]; EU limits for soil amended with sewage sludge [7], Annex IA) and soil guideline values in the EU [23]; all in mg/kg dry soil

Soil amendment limits						Soil quality limits			
Element	EU [10]	0	I	II	III	[12]	[13]	[7]	[23]
As	–	*5*	*8*	*16*	*32*		8	–	100–200
As_i	40	–	–	–	–	–	–	–	–
Cd	1.5	0.4	0.8	2.0	5.0	1.0	1.5	1.0–3.0	0.5–20
Cr(VI)	2	–	–	–	–	–	2	–	–
Cr	–	50	60	100	150	100	50	–	30–1000
Cu	300	50	150	650	1000	50	100	50–140	40–1000
Hg	1.0	0.2	0.6	3.0	5.0	1.0	1.0	1.0–1.5	0.5–80
Ni	50	20	30	50	80	30	60	30–75	30–300
Pb	120	40	60	80	200	50	60	50–300	40–750
Zn	800	150	400	800	1500	150	200	150–300	60–2500

As_i = inorganic arsenic. Norwegian limits for arsenic, in italics, were proposed in 2024 . [12, 20]; limits given in the regulation on restriction of pollution [13]; EU limits for soil amended with sewage sludge [7], Annex IA) and soil guideline values in the EU [23]; all in mg/kg dry soil for soil amended with sewage sludge, not for soil receiving organic amendments in general. For example, in Denmark, it is explicitly mentioned in the national regulation for organic waste application on agricultural land that the PTE concentration limits do not apply to green waste composts or animal manure [3]. The Norwegian regulation does not restrict the soil quality limit to soil where sewage sludge is applied, but the regulation is not strictly controlled and hence most growers are not aware of the soil PTE limits.

Amounts of fertilisers required for carrots

For all selected fertiliser materials, much higher amounts must be applied to cover the demand for K than for N or P (Fig. 2). On a DM basis, 2.3 kg of SSOW compost, 0.19 kg of SSOW digestate, 3 kg of green waste compost, 1.4 kg of horse manure and 0.3 kg of commercial fertiliser with poultry manure was required to cover the K demand. As shown in Table 5, the composts and poultry manure were Class I soil amendments [12] due to the concentration of Cd, Zn or both, and horse manure was Class I due to Cu. For these materials, a limit of 0.4 kg DM m^{-2} annually is posed by the restrictions in [12]. A rate of 0.4 kg DM m^{-2} annually would not cover the crop demand for N with any recycled material except the SSOW digestate. This material was Class II due to high content of Zn, with a limitation of 0.2 kg DM m^{-2} annually. The requested amount of SSOW digestate was 189 g m^{-2} annually (Fig. 2). However, with the very low content of dry matter (about 2%, Table 4), this amount would require an extremely high application of 8591 g digestate per m^2. This is not realistic in practice, but for the calculation we maintained the amount. None of the Norwegian PTE values were above the upper limit for organic fertilisers in the EU [10].

Assessing PTE concentrations in soil with applied fertiliser amounts

While the hypothetical applications of fertiliser materials required to cover the nutrient demand of carrots would not be permitted in Norway, they would not be restricted by the regulation for PTEs in organic soil conditioners the EU [10]. The horse and poultry manure applications would be restricted by the nitrate directive where maximum 170 kg N ha^{-1} from manure may be applied per year [9]. Despite this, we have calculated the theoretical increase in soil PTE concentrations also with these materials.

The time required to reach the maximum concentration of various PTEs for each fertiliser in the Bergen and Oslo regions is shown Fig. 3, without any consideration of PTEs removed from the soil by leaching/runoff or plant uptake. It is evident that soils with higher content of organic matter, as found near Bergen, are discriminated when the thresholds for PTEs in soil are set on a weight basis. For Cu, it would take 50 years with intensive application of horse manure to reach the soil quality limit in the Oslo region, but only 18 years in the Bergen region. With a low bulk density value, the calculated soil concentrations will increase faster, and the Bergen region reaches the limits much faster than the Oslo region for all PTEs.

In both regions, the PTEs which would first reach the soil quality thresholds are As, Cu and Zn. Since the concentrations of As were few, the results must be treated very carefully for this element, but the result indicates that more analyses are required. While being toxic at

Time to reach PTE soil quality treshold, years				
1-50	51-100	101-500	501-1000	>1000

PTE	SSOW compost		SSOW digestate		GOW compost		Horse manure		Poultry manure	
	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo
As	32	50	393	605	24	38	341	526	2128	3280
Cd	67	128	898	1703	51	97	183	347	2128	4037
Cr	489	652	9473	12652	127	170	606	809	11806	15768
Cu	34	96	340	962	24	69	18	50	476	1346
Hg	1123	1499	27312	36473	638	852	3798	5072	47358	63242
Ni	108	162	2355	3519	49	72	156	234	3252	4859
Pb	200	347	3564	6196	57	100	96	167	17987	31270
Zn	43	54	172	218	24	30	80	101	221	280

Fig. 3 Visualisation of the time required to reach the soil quality limit for each PTE with each fertiliser material (years), when plant uptake and leaching/runoff was not included. SSOW = source-separated organic waste from private households, catering and retail. GOW = green organic waste compost

high concentrations, Cu and Zn are also essential micronutrients for crop plants, animals, and humans. The element of possibly highest concern is Cd, where threshold values would theoretically be reached in 50–100 years with application of compost, and 200–400 years for horse manure. Horse manure would also theoretically cause a reaching of the thresholds for Pb and Ni in 100–200 years.

The commercial poultry manure product had the highest concentration of nutrients compared with PTEs. Horse manure has a relatively high content of Pb, Ni and Cd, in addition to the mentioned high concentrations of Cu and Zn. Green waste compost generally has the lowest concentrations of nutrients compared with PTEs, and soil quality limits would theoretically be reached in less than 100 years for all PTEs except Cr and Hg, in both regions. Composted food waste has more nutrients compared with PTEs than composted green waste. As discussed above, digested food waste has a remarkably low concentration of PTEs on a DM basis and could be applied for more than 170 years before reaching soil quality tresholds (for Zn). However, this product is difficult to apply in practice in its present form, and we need much more analytical values for the chemical composition of this fertiliser where dry matter concentrations are highly variable and difficult to measure.

In practice, growers will not apply the mentioned amounts of fertiliser materials, and PTEs will not accumulate in soil over time as supposed. To assess at least two important factors which will affect the concentrations of PTEs in soil over time, we repeated the calculation, subtracting the PTEs removed in the carrot crop applying data from [15], and in combined leaching and runoff applying data from [28].

As expected, the subtraction of plant uptake and leaching/runoff increased the number of years requested to reach soil quality limits (Fig. 4). In several cases, negative values were obtained, implying that the soil concentration would decrease over time (Fig. 4). This was often when the initial calculation gave high values of time requested to reach the limit soil concentration, but not always. The subtraction changed the assessment significantly especially for Cd and Ni, and to some extent for Zn. As, Cu and Zn were still the elements where soil quality limits would first be reached. The number of years to reach the limits were only slightly increased for these elements, and for Pb.

When the calculation was repeated with the upper limits of the EU regulation for sewage [7], the number of years increased to above 50 in all cases (no red colour, Fig. 5), and only Zn and Cu remained of concern within a period of 100–200 years.

Discussion

The calculations demonstrated that soil concentrations of PTEs may increase significantly, if a situation occurs where the plant nutrients must be applied via recycled fertiliser products. The soil quality limits were first exceeded for Zn and Cu, within 20–85 years (Fig. 4). For As, more analytical data is required. Very high applications of organic fertiliser materials may occur in a situation of global crisis, which recent events like Covid have shown may not be unlikely. The effect of crop uptake and leaching reduced the accumulation rate for some elements (Cd, Cr, Ni), whereas for other elements (As, Cu, Hg, Pb, Zn) this did not have any large effect on the theoretical accumulation. With better management of materials during composting, nutrient concentrations may increase, reducing the need for extremely high applications. It may also be an option to combine the urban waste-based fertilisers with materials high in K to reduce the application levels. Potassium may be applied from mineral K fertilisers, but this is a non-renewable resource, and reserves are expected to peak within less than 100 years [22]. Seaweeds could possibly be a relevant source of K, not least in Norway with a long coastline,

PTE	SSOW compost		SSOW digestate		GOW compost		Horse manure		Poultry manure	
	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo
As	43	57	-187	-1276	30	42	-202	-1868	-135	-469
Cd	-41	615	-26	-178	-51	242	-30	-300	-26	-168
Cr	1368	1552	-826	-1235	153	200	2995	2882	-812	-1212
Cu	44	102	-248	2546	29	72	20	52	-215	10411
Hg	1210	1521	-35764	56349	665	859	5033	5334	-23010	162835
Ni	-70	-103	-43	-64	-352	-481	-59	-86	-43	-64
Pb	310	373	-663	-24326	64	102	116	173	-577	-5865
Zn	85	74	-167	-2083	33	35	1463	209	-137	-664

Fig. 4 Visualisation of the time required to reach the soil quality limit for each PTE with each fertiliser material (years), when plant uptake and leaching/runoff was subtracted from the annual application of PTEs. SSOW = source-separated organic waste from private households, catering and retail. GOW = green organic waste compost. Colour legend shown in Fig. 3

PTE	SSOW compost		SSOW digestate		GOW compost		Horse manure		Poultry manure	
	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo	Bergen	Oslo
Cd	-248	2666	-158	-770	-308	1048	-179	-1302	-155	-727
Cu	279	344	-1562	8575	185	243	127	174	-1293	35068
Hg	1890	2330	-55857	86322	1039	1316	7860	8171	-35938	249449
Ni	-358	-461	-221	-286	-1790	-2146	-298	-385	-220	-285
Pb	3544	3201	-7570	-208786	729	872	1324	1482	-6587	-50298
Zn	252	218	-493	-6141	97	104	4313	615	-405	-1958

Fig. 5 Visualisation of the time required to reach the soil quality limit for PTEs except As and Cr (no limits in EU 1986) with each fertiliser material (years), when plant uptake and leaching/runoff was subtracted from the annual application of PTEs and upper limits in the regulation EU1986 was applied. SSOW = source-separated organic waste from private households, catering and retail. GOW = green organic waste compost. Colour legend shown in Fig. 3

since they have a high content of minerals compared with terrestrial plants. Up to 40% of their DM may be ashes, as compared with maximum 20% for mineral-rich vegetables like spinach [4]. Brown algae common along the Norwegian coast such as kelp (*Saccharina latissima*) may contain K up to 8% of the total solids (which comes close to DM), and rockweed (*Ascophyllum nodosum*) up to 12%, dependent on season [21]. Hence, brown macroalgae may be suitable for fertiliser extraction. However, K will be accompanied by other minerals such as sodium, which is not beneficial for soil quality and crop growth, and PTEs like arsenic and cadmium. K may also be supplied by human urine.

If K is supplied from other sources, the amount of fertiliser material will be decided by the demand for P or N. Both nutrients are less readily available for plant uptake when applied as an organic material compared with mineral fertilisers. Hence, for P it may be relevant to apply quite high amounts in soils with low extractable P concentrations, since for this nutrient it is possible to accumulate nutrient reserves in the soil. However, the amounts should not be too high, since for N, mineralisation may occur after crop nutrient uptake, or mineral N may be lost before plant uptake. Hence, N should not be applied only with fertiliser materials that need a long mineralisation period. For N demanding crops (like carrot), additional fertilisers may be applied, and again, human urine may be a relevant solution in a peri-urban context. This will also supply P. A recent study from Barcelona [24] calculated that struvite (magnesium ammonium phosphate) precipitation installed in two large wastewater plants, dependent on technology, could recover enough P to cover 5–30 times the demand in the agricultural region being studied (36.5 tons).

The amount of N applied per m^2 if the highest amount of material were applied, would be 49, 32, 31, 18 and 26 g for the fertiliser materials selected here, corresponding to 490–180 kg N ha^{-1} (Fig. 2). While these are high rates of N, such high applications of soil amendment materials may not be unrealistic in small-scale vegetable growing. Composts and grass clippings are often applied as a mulch cover to reduce the need for weeding. One case farm grower applied about 5 kg m^{-2} of composted horse manure. With a DM content of 35%, this would be 1750 g DM m^{-2}. With a bulk density of 0.5 kg per litre, the amount would correspond to a 1 cm thick layer. Recommended compost application in small-scale growing is often much higher. E.g., [26] proposed a compost layer of 2.5–8 cm for gardening, preferably to be mixed into the soil, and [17] recommended 7.5–10 cm for new garden beds and 0.5–2.5 cm for maintenance of existing beds. With such high applications of organic materials, the growers should monitor soil concentrations of PTEs regularly.

As shown, the limits of PTE concentrations in soil amendments set in Norwegian regulations are significantly stricter than in the EU. This significantly restricts the application of all selected materials to amounts well below those required by crop plants. This limits the possibility for growers to utilise locally available materials, while imported mineral fertilisers may be applied in amounts complying with crop demands. Norwegian policy makers should consider an adaptation to EU regulations which support recycling of valuable nutrients and organic matter to a much larger extent.

The soil quality limits in Norway [12] are similar to the lower limit of values set to control the application of sewage sludge in the EU [7], but in Norway the soil limits govern all types of organic soil amendments. Several agricultural soils have PTE concentrations above the soil quality limits caused by local geology, commonly for Ni [28], which is of small concern. On such soil, organic amendments sourced from outside the farm may not be applied. This may have significant negative effects on soil health and quality, especially on arable farms. The soil quality limits are well below the maximum soil guideline values [23]. If the maximum soil quality limits were applied, the time periods calculated above would be extended to 750–1000 years for Zn for the green waste compost, and to more than 1200 years for all other combinations of PTE and fertiliser material when no subtraction is made for plant uptake and leaching/runoff. If the soil quality limits were set at the upper EU limit for soil amended with sewage sludge and plant uptake + leaching/runoff is subtracted, limits for Cu and Zn would be reached in 100–200 years with composted urban waste (Fig. 5), as compared with 20–85 years with the lower limit applied in the Norwegian regulation. In a long-term perspective, this is not a very significant difference in time. This points to that the contents of these PTEs is of special importance to monitor, to reduce inputs to the food chain. This result is well in line with [1], who found that the concentrations of these elements would increase more rapidly than for other elements with intensive use of organic waste as fertiliser, especially on sandy soils. The current soil quality limits in the Norwegian legislation are strict as compared with EU regulations, especially since all organic materials are included. As shown [28], many regions in Norway have agricultural soils with PTE concentrations well above the soil quality limits. A complete ban of organic soil amendments sourced from outside the farm on all such area is questionable with respect to soil health and quality. Other solutions could be found, e.g. that the soil quality limit for one specific PTE only pertains to organic soil amendments with a relatively high concentration of this PTE.

Agricultural soil should in principle be available for food and feed production over infinite time periods. It is not possible to state how long time periods before the soil concentrations exceeds a certain level that are acceptable. The concentrations of PTEs in recycled organic materials should be monitored, and reasons for concentrations which exceed formerly determined values, regional or national averages or typical values, should be explored to ensure that sources of pollution are minimised. In addition to animal feed and housing, this could be materials entering the organic waste value chain because of poor separation procedures, or during the treatment, e.g., due to corrosion of metals by organic acids during composting or mechanical wear of equipment during turning of compost [2].

Conclusions

Norwegian regulations for PTE concentrations in organic fertilisers and soil amendments are significantly stricter and more detailed than the EU regulation. All urban waste-based fertiliser materials assessed in the present study had concentrations of PTEs hampering their application as fertilisers according to crop nutrient demand, while none of the fertiliser materials had PTE concentrations above the limits for organic fertilisers in the EU legislation. Further, whereas more liberal upper values for PTEs in EU regulations for soil quality would not make a very large difference, the Norwegian legislation prohibits any use of organic soil amendments on soil exceeding the limits, and not only sewage sludge. This is a significant difference that calls for justification.

All in all, the Norwegian regulations of PTEs in soil amendments and soil clearly hamper the recirculation of organic matter and nutrients.

The two elements which most commonly lead to excess application levels are Zn and Cu. Means should be taken to reduce the input of these metals to the food chain, while keeping in mind that they are also essential plant nutrients.

Urban waste-based fertilisers are not well balanced with respect to the nutrient demand of a typical horticultural crop (carrots). The content of K is too low, and all the described fertilisers would require a very high application to cover the demand for K, leading to significant surplus of N and P. Potassium might be supplied from additional sources, but care should also be taken to avoid all losses of K during processing and storage of fertiliser and soil amendment materials, since K is easily leached.

While not being environmentally or agronomically sound in large scale, the high applications described here are not unlikely in small-scale growing. Soil quality limits will be reached relatively fast (20–85 years) if such high amounts of materials are applied. The limits are first reached for Cu and Zn.

Soils with a low bulk density due to high content of organic matter, are discriminated with respect to soil quality limits when PTE contents are governed by weight.

Growers who want to utilise urban waste-based fertilisers intensively should monitor their soil regularly and include analyses of PTEs. Soil sampling should occur on fixed sampling points to reveal changes in concentrations over time.

Norwegian authorities should consider a revision of the organic fertiliser regulation to support recycling of valuable organic materials, and there is a need for more data on the concentrations of PTE values in agricultural soil and organic fertiliser materials.

Acknowledgements

We are grateful for the efforts conducted by the participating case farmers. We are also grateful to Trond Haraldsen, NIBIO for providing analytical data of urban waste fertiliser materials, and to anonymous reviewers for contributing to the publishing of this study.

Author contributions

SE designed the project and selected the case farms and amended the manuscript in several steps. AKL conducted the soil analysis, compiled the literature, conducted the calculations and interpreted the data. TR checked the data and designed the figures and made important remarks to the design. All authors read and approved the final manuscript.

Funding
Open access funding provided by Norwegian Institute of Bioeconomy Research. The paper was written with funding from the BIONÆR programme of the Research Council of Norway, grant no. 294604 for the project URBAN-FARMS (2019–2023). Chemical analyses of organic waste products used in this paper were provided from the project "Recycling organic waste—effects on soil quality, plant nutrient supply and environmental impact", supported by the Research Council of Norway, grant no. 173496/I30.

Data availability
The dataset applied in the current study will be made available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests, and do not possess shares or board positions in any type of industry which may potentially benefit from increased sales of organic waste as soil amendments.

Author details
[1]NORSØK – Norwegian Centre for Organic Agriculture, Gunnars Veg 6, 6630 Tingvoll, Norway. [2]NIBIO – Norwegian Institute of Bioeconomy Research, PO Box 115, 1431 Ås, Norway.

Received: 8 October 2024 Accepted: 13 October 2024
Published online: 20 November 2024

References
1. Amlinger F (2004). Heavy metals and organic compounds from wastes used as organic fertilisers. Report to the European Commission, DG-Environment. Report/Project ENV.A.2./ ETU/2001/0024. European Commission, DG, Environment, Brussels, Belgium
2. Amundsen CE, Lystad H, Vethe Ø (2002) Kilder til forurensninger i kompost (in Norwegian). Jordforskrapport nr. 69/2002, 41 p
3. BEK nr 1001/2018 Bekendtgørelse om anvendelse af affald til jordbrugsformål (in Danish). https://www.retsinformation.dk/eli/lta/2018/1001 Accessed 3 Sep 2024
4. Circuncisão AR, Catarino MD, Cardoso SM (2018) Silva AMS (2018) Minerals from macroalgae origin: health benefits and risks for consumers. Mar Drugs 16:400
5. Daugstad K, Øverli KA, Nesheim L (2012) Næringsinnhald i husdyrgjødsel. Analyser av husdyrgjødsel frå storfe, sau, svin og fjørfe 2006–2011 (in Norwegian). Bioforsk Rapport Vol. 7 Nr. 24, 2012, 29 p.
6. Egnér H, Riehm H, Domingo WR (1960) Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden (in German). Kungl Lantbrukshögskolans Annaler 26:199–215
7. European Commission (EC) (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. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31986L0278 Accessed 3 Sep 2024
8. European Commission (EC) (2020) Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU Biodiversity Strategy for 2030: Bringing nature back into our lives, section 2.2.8: Greening urban and peri-urban areas. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN Accessed 25 May 2023
9. European Commission (EC) (2022) Fighting water pollution from agricultural nitrates. Summary of directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. https://eur-lex.europa.eu/EN/legal-content/summary/fighting-water-pollution-from-agricultural-nitrates.html Accessed 25 May 2023
10. European Union (2019) 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. http://data.europa.eu/eli/reg/2019/1009/oj Accessed 15 Feb 2024
11. Extreme Weather Watch (2024) https://www.extremeweatherwatch.com/cities/bergen/average-rainfall-by-month. Accessed 11 July 2024
12. FOR-2003-07-04-951 Forskrift om gjødselvarer mv. av organisk opphav (in Norwegian). 2024 https://lovdata.no/dokument/SF/forskrift/2003-07-04-951/ Accessed 15 Feb 2024
13. FOR-2004-06-01-931 Forskrift om begrensning av forurensning (in Norwegian). https://lovdata.no/dokument/SF/forskrift/2004-06-01-931/ Accessed 15 Feb 2024
14. Hawes JK, Goldstein BP, Newell JP et al. (2024) Comparing the carbon footprints of urban and conventional agriculture. Nat Cities 1:164–173. https://doi.org/10.1038/s44284-023-00023-3
15. Krejčová A, Návesník J, Jičínská J, Černohorský T (2016) An elemental analysis of conventionally, organically and self-grown carrots. Food Chem 192:242–249. https://doi.org/10.1016/j.foodchem.2015.07.008
16. Milford AB, Prestvik AS, Kårstad S (2021) Markedshager i Norge. Utfordringer og muligheter med småskala grønnsaksproduksjon for direktesalg (in Norwegian). NIBIO Report Volume 7 No 153. 63 p.
17. Miller W, Mann JJ (2021) How to use compost in gardens and landscapes. Oregon state university extension service. https://extension.oregonstate.edu/pub/em-9308 Accessed 25 May 2023.
18. Möller K, Schultheiss U (2014) Organische Handelsdüngemittel im Ökologischen Landbau (in German). KTBL-Schrift 499. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), Darmstadt, Germany
19. Norwegian Environment Agency (2024) Normverdiar for forureina grunn (in Norwegian). https://www.miljodirektoratet.no/ansvarsomrader/kjemikalier/kjemikaliesok/normverdier-for-forurenset-grunn/ Accessed 15 Feb 2024
20. Norwegian Food Safety Authority (NFSA) (2024) Utkast til forskrift om produksjon, omsetning og import av gjødselvarer av organisk opphav og visse uorganiske gjødselvarer (gjødselvareforskriften) (in Norwegian). https://hoering.mattilsynet.no/Hoering/2963 Accessed 4 Sep 2024
21. Ometto F, Steinhovden KB, Kucic H, Lunnbäcka J, Berga A, Karlsson A, Hand A, Wolland H, Ejlertsson H (2018) Seasonal variation of elements composition and biomethane in brown macroalgae. Biomass Bioenerg 109:31–38
22. Rawashdeh RA (2018) World peak potash: an analytical study. Res Policy 69:101834
23. Reimann C, Fabian K, Birke M, Filzmoser P, Demetriades A, Negrel P, Oorts K, Matschullat J, deCaritat P (2018) GEMAS: Establishing geochemical background and threshold for 53 chemical elements in European agricultural soil. Appl Geochem 88:302–318
24. Rufí-Salís M, Brunnhofer N, Petit-Boix A, Gabarrell X, Guisasola A, Villalba G (2020) Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions. Sci Total Environ 737:139783
25. Semb G (1985) Investigations of the influence of soil bulk density on soil tests. Comparison of analytical figures based on extraction of a certain weight or volume of soil (in Norwegian). Jord og myr 9:69–79
26. Spengler T (2022) Using composts in gardens—how much compost is enough. Gardening KnowHow https://www.gardeningknowhow.com/composting/basics/how-much-compost-is-enough.htm Accessed May 25, 2023.
27. Statistics Norway (2023) Holdings, agricultural area and livestock. https://www.ssb.no/en/jord-skog-jakt-og-fiskeri/jordbruk/statistikk/gardsbruk-jordbruksareal-og-husdyr Accessed 15 Feb 2024
28. VKM (Norwegian Scientific Committee for Food and Environment) Eggen T, Amlund H, Barneveld R, Bernhoft A, Bloem E, Eriksen GS, Flem B, Källqvist T, Sverdrup LE, Trapp S, Øgaard AF, Fæste CK, Lock EJ, Ringø E, Steinshamn H, Ørnsrud R, Krogdahl Å (2022) Risk assessment of potentially toxic elements (heavy metals and arsenic) in soil and fertiliser

products – fate and effects in the food chain and the environment in Norway. Scientific Opinion of the Panel on Animal Feed of the VKM. VKM report 2022:09. Norwegian Scientific Committee for Food and Environment (VKM), Oslo, Norway.
29. Weissengruber L, Möller K, Puschenreiter M, Friedel JK (2018) Long-term soil accumulation of potentially toxic elements and selected organic pollutants through application of recycled phosphorus fertilizers for organic farming conditions. Nutr Cycl Agroecosyst 110:427–444
30. Yara (2020) Gjødselhåndbok (in Norwegian). Page 70. https://www.yara.no/siteassets/crop-nutrition/gjodslingsrad/yara_gjodselhandbok_2020.pdf/ Accessed 3 Mar 2023
31. Yang JL, Zhang GL (2015) Formation, characteristics and eco-environmental implications of urban soils – Areview. Soil Science and Plant Nutrition, 61(sup1), 30–46. https://doi.org/10.1080/00380768.2015.1035622

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.