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Microplastic pollution in agricultural soils and abatement measures – a model-based assessment for Germany

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Abstract

Microplastic pollution in soils is a recent environmental problem and the lack of knowledge about the impacts and the extent of the problem are raising questions and concerns among researchers and politicians. Using a normative simulation model, we assess the extent of microplastic pollution in German agricultural soils originating from the land application of sewage sludge and compost. We estimate the microplastic concentration in German agricultural soils, the area of polluted land, and we compare the efficiency and effectiveness of some selected abatement measures. For 2020, we estimate that microplastic concentration in agricultural soil reaches a maximum concentration of between 30 and 50 mg/kg dry weight on 2% of Utilised Agricultural Area and a marginal concentration on 22% of Utilised Agricultural Area. Without the implementation of abatement measures, we expect the microplastic concentration to increase two to three times by 2060. Assessing the abatement measures, we find that for sewage sludge, thermal recycling is a more efficient and effective than equipping washing machines with microplastic-filters in private households. The use of plastic detection systems in the biowaste collection process reduces the plastic content of the compost and thus the release of microplastic into the soil. Detection systems are a more efficient measure for compost than thermal recycling. Concerning sludge, the findings indicate that the German strategy of thermally recycling sewage sludge is an efficient and effective measure to reduce microplastic pollution in soils. Reducing the plastic content of collected biowaste complies with the principles a circular economy.

Keywords

Mitigation cost, Efficiency, Recycling, Fertiliser, Sewage sludge, Compost

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1 Introduction

Microplastic pollution is a recent challenge for environmental research and policy. Today, microplastics, which are commonly defined as solid plastic particles of the size between 1 and 5000 μm , occur in nearly all environmental systems (e.g., [1–3]). More than 15 years ago, in 2005, Zubris and Richards [4] had already found microplastics in agricultural soils in the form of textile fibres originating from sewage sludge [5]. The potential environmental threat posed by microplastics to soils has recently come under greater scrutiny (e.g., [6–9]). Research concerning the sources, processes, fates, sinks, exports and impacts of microplastics is lacking [10, 11]. Researchers consider the land application of sewage sludge and compost as organic fertilisers and as an important pathway for the emission of microplastics into agricultural soils [7, 12]. Farmers apply sewage sludge and compost as organic fertiliser and provide a waste disposal service to the society. Thus, they unintentionally emit microplastics to soil without environmental regulations being in place to protect them from this pollution. Hence, farmers are in the ambivalent position of being both victims and polluters [13]. However, the lack of scientific evidence on the pollution potential and impacts of these substances to date, delays the design and implementation of environmental policies aiming to reduce the pollution of agricultural soils with microplastics [14].

Microplastics are suspected to have negative impacts on soils ecosystems. They can change the physical characteristics of soils [9, 15] and release associated toxic chemicals (e.g., additives, cf. [16]). They can also act as vectors for environmental contaminants like pesticides, heavy metals and antibiotics [17]. Furthermore microplastic particles can be ingested by soil organisms. At the nano-scale size, microplastics may even cross biological barriers [3, 12, 18]. The high stability of plastic as a material means that its decomposition (degradation) under natural environmental conditions is extremely slow. Researchers therefore anticipate an accumulation of microplastic in environmental systems (e.g., in soil and water) [2, 19–21]. Environmental assessment and policymaking processes require information on the status of microplastic pollution and on potential abatement measures to reduce this pollution. This paper assesses the presence of microplastic pollution in agricultural soils in Germany originating from the agricultural use of sewage sludge and compost under various polluting scenarios. It presents an economic assessment of various abatement measures for the reduction of microplastic emissions from these sources.

In Germany, farmers use sewage sludge and compost as soil amendments to help improve soil structure and as organic fertilisers. At the same time, farmers provide German society with a waste disposal service [13]. Microplastics are emitted into sewage sludge and compost from private households and different industries. Microplastics enter wastewater from households and industry (e.g., cleaning products, fibres from synthetic textiles). Sewage sludge, a residue from the wastewater treatment process, contains these microplastics [22–24]. The microplastics present in compost originate from private households, industry and landscaping because plastic materials (e.g., food packaging, littered plastic in landscaping clippings) are not (sufficiently) separated from the organic waste before collection and composting. The compost producer can only remove plastic particles down to a certain size through screening, meaning that the separation process is not efficient in removing the smaller plastic fragments (e.g., small thin fragments of plastic film from food packaging). Mechanical processes used during the composting process (e.g., shredding and mixing), degrade the macro plastic fragments into microplastic sized particles [25, 26].

A growing number of analytical studies in environmental research and natural science literature refers to the measurement of microplastics in soils and organic fertilisers. Microplastics occur in soils in relatively low concentrations and separating them from soil particles is difficult. Thus, researchers face the challenge of developing methods to accurately measure microplastics in soils and to conduct measurement-based impact assessments [27–29]. Model-based impact analysis provides information unobtainable by measured values, particularly at the sectoral and regional levels, and numerical modelling is used to assess environmental problems in aquatic environments [30]. However, to date, only a few studies apply quantitative modelling approaches to estimate microplastic emissions from land-based sources.

Using an economy-wide balance model, Bertling et al. [31] quantify the microplastic emissions from the most significant sources into the environment in Germany and report on the sources that are relevant for wastewater and compost. The focus of this study is however not on soil pollution. Kawecki and Nowack [32] apply a material flow analysis to quantify the microplastic emissions in Switzerland from different processes and products. The authors differentiate between macro and microplastics of different polymer types, from the most relevant sources (products and processes) and the emissions into water and soils. Conversio [33] simulates the economy-wide microplastic emissions relevant to riverine systems flowing into the North and Baltic seas using a top-

down balance model. Specifically, they consider the regional microplastic emissions from land-based application of sludge and compost in agricultural production and landscaping. Finally, Brandes et al. [34] focus their analysis on the emissions of microplastics from sewage sludge and compost into German agricultural soils. Using a normative top-down model, they estimate the quantities of emitted microplastic at the sector level and the concentration of microplastics in the soil at the regional level. The analysis allows for the identification of regional hot-spots with a high concentration of microplastics.

Our study extends the scope of the cited studies by exploring the following new research questions:

1. What is the extent of the pollution potential of microplastics in agricultural soils from sewage sludge and compost in terms of concentration and polluted area? In addition to the concentration of microplastic covered by the cited studies, we also quantify the size of the area in which microplastic pollution can be found.
2. How significant is the concentration of microplastic in soils and the polluted area under different assumptions of sludge and compost fertilisation intensities? The cited studies provide results for a reference year under unchanged pollution conditions. We simulate the results for a series of potential pollution scenarios by varying fertilisation intensity assumptions for sewage sludge and compost.
3. How efficient and effective are different abatement measures to reduce microplastic emissions from sewage sludge and compost? Information on abatement measures is valuable for designing and evaluating environmental policies against microplastic pollution. Therefore, we assess four selected abatement measures: thermal recycling (end-of-pipe measure, for microplastics in sewage sludge and biowaste/compost), filters in washing machines and detection techniques in biowaste collection (source reduction measures for sewage sludge and biowaste/compost).

The rest of the paper is structured as follows: Section 2 introduces the normative models we use to simulate both the pollution and the abatement measures. In Section 3, we present and discuss the results of the simulated pollution scenarios and abatement measures. Finally, Section 4 concludes with policy recommendations and suggestions for future research work.

2 Methodology

We developed a normative emission model for Germany to estimate the quantities of microplastic released from sewage sludge and compost and the concentration of microplastic accumulated in agricultural soils. The data used in the model and the assumptions made are derived from literature and statistics. We compute the average costs associated with the abatement measures and estimate the abatement effect.

2.1 Estimating microplastic concentrations

A few analytical studies report on the microplastic content of sewage sludge. We use the mass-based emission microplastic quantities provided by Bertling et al. [31] for the relevant sources for emissions of microplastics into wastewater and sewage sludge: textiles, cosmetics, cleaning substances and personal care products. Bertling et al. [31] estimate that the empirical filtering rate of microplastics in wastewater treatment processes to be between 95 and 99% [31]. Defining the model's filtration rate at 95%, we assume that 5% of the microplastics leave the treatment plant into aquatic systems with the treated wastewater. Based on the 95% filtering rate, we compute an average microplastic content in the sludge of 0.6% dry weight for the reference year 2016. Other studies report lower microplastic concentrations, ranging from average values of 0.05 to 0.1% dry weight [35] to 0.4% dry weight [36]. Thus, the 0.6% dry weight concentration of microplastic in sludge is relatively high and so represents a 'worst-case' scenario for Germany. Eq. 1 describes the calculation of microplastics in sewage sludge from the selected sources for the reference year 2016:

$$MPCONC_{sludge} = \left(\frac{\sum_{source} MPEM_{source} POP_{2016}}{Q_{sludge,2016}} \right) FR \quad , \quad (1)$$

with

$MPCONC_{sludge}$: concentration of microplastics in sewage sludge as % dry weight,

$MPEM_{source}$: annual emissions of microplastics per capita in 2016 expressed as g/(head year), i.e., computed, based on Bertling et al. (2018) textile fibres from households and industry = 76.8 g/(head year) (or 57% of total); industrial cleaning = 23 g/(head year) (or 17% of total); cosmetics = 19 g/(head year) (or 14% of total); abrasives in pipes = 12 g/(head year) (or 9% of total); cleaning products and personal care products = 4.6 g/(head year) (or 3% of total),

POP_{2016} : population in Germany in 2016 = 82.3 million inhabitants,

$Q_{sludge,2016}$: quantity of sewage sludge produced in 2016 in g dry weight,

FR : filtration rate = 95%.

The amount of microplastic in wastewater is calculated from the emissions from various household and industrial sources. Thus, we assume that the amount of microplastics in wastewater and sewage sludge has changed from 1983 to 2016. To consider the concentration of microplastics over time, we use the global development of polyester production. Since synthetic fibres are the primary source of microplastics in sludge, we use this index as the basis for all calculations of microplastic concentrations in wastewater and sewage sludge (see Appendix A-1.0 for further details.).

Few empirical studies analyse the concentration of microplastics in compost. Weithmann et al. [26] found particle numbers ranging from 14 to 895 items/kg dry weight in the size range of between 1 and 5 mm in different types of composts. Bläsing and Amelung [25] measured a concentration of microplastics in compost samples ranging from 2.38 to 180 mg/kg dry weight, in the size range of between 1 and 5mm. This corresponds to a mean value of 0.008% dry weight. For this study, we consider the concentration of microplastics in compost according to Kehres [37]. Kehres [37] quantifies the concentration of plastic particles larger than 2 mm at 0.032% dry weight in certified composts. Kehres [37] estimates that the concentration is 10% higher when considering the size fraction range of between 1 and 2 mm [37, 38]. Thus, we derive a concentration of microplastic in compost to be 0.04% dry weight¹ for the particle size range of between 1 and 5mm. Assuming the worst-case scenario, we select the highest concentration of 0.04% dry weight as representative for Germany.

We assume that over time between 1983 and 1990, the concentration of microplastic in sewage sludge has changed and we use the emission factor ($EF_{sludge,t}$) to represent the evolution of microplastics in sewage sludge. Due to the lack of information on the evolution of the plastic content of biowaste, we assume that the emission factor for compost ($EF_{compost,t}$) is constant over time. Eq. 2 computes the emission factors ($EF_{f,t}$) for the organic fertiliser (f) in the year (t):

$$EF_{f,t} = MPCONC_f * DEV_{f,t} \quad , \quad (2)$$

with

$EF_{f,t}$: Emission factor for the organic fertiliser (f) for the year (t),

$MPCONC_f$: Concentration of microplastic in the organic fertiliser (f), sewage sludge = 0.6% dry weight, compost = 0.04% dry weight,

$DEV_{sludge,t}$ = Scaling factor applied to the 2016 microplastic concentration in sewage sludge according to evolution of textile fibres, see Appendix A-1.0, for details.

$DEV_{compost} = 1$.

2.2 Estimating microplastic emissions

We develop a normative emission model at the sector scale to estimate the quantities of microplastics emitted from sewage sludge and compost into agricultural soils. The model considers sewage sludge and compost and excludes all other sources of microplastics (e.g., plastic films). The model (Eq. 3 to 7) simulates the emissions of microplastics according to current legislation on the land application of sewage sludge and compost. The model is, therefore, a normative emission model.

In Eq. 3, the sector emission factor $EF_{f,t}$ expresses the concentration of microplastic in the fertiliser, with $EF_{sludge,t}$ increasing from the year 1983 to 2016 to 0.6% of dry weight in 2016 (Figure 1) and with $EF_{compost,t}$ as a constant concentration from 1990 to 2016 at 0.04% of dry weight. Eq. 3 computes the quantity of microplastic emitted for the year t and from fertiliser f (sewage sludge or compost):

$$QMP_{f,t} = QF_{f,t} * EF_{f,t} \quad , \quad (3)$$

with

$QMP_{f,t}$: Quantity of microplastics emitted from fertiliser (f) in the year (t),

$QF_{f,t}$: Quantity of fertiliser used (f) in the year (t) in tons of dry solids,

$EF_{f,t}$: Emission Factor for microplastic emissions from fertiliser (f) in year (t),

f : Fertiliser used; either sewage sludge or compost,

t : The simulated year = (1984,...,2016).

We assume that microplastics emitted from sewage sludge and compost accumulate in the soil over time. Due to the lack of knowledge on relevant processes, we exclude any metabolisation of microplastics and presume no losses occurring through wind and water erosion. Eq. 4 describes the cumulated quantities of microplastics released into the soils in the simulated year t by summing up the quantities of microplastics emitted over the past years:

¹i.e., $0.032\% + 10\% \cdot 0.032\% = 0.035\% \sim 0.04\%$

$$QMPS_{f,T} = \sum_{t_0}^T (QMP_{f,t_i}) \quad , \quad (4)$$

with

t_0 : The first year of a simulation period, for sludge = 1983, for compost = 1996,

t_i : The simulated year, for sludge = (1984, 1985, ..., 2016), for compost = (1996, 1997, ..., 2016)

T : The last simulated year of a simulation period = (1985, ..., 2016),

$QMPS_{f,T} = QMPS_{f,t}$: Cumulative quantity of microplastic emitted to soils from fertiliser f (sewage sludge, compost) over time for the simulated year t .

Based on normative assumptions of the maximal application of fertiliser f , we define three fertilisation intensity scenarios: high, medium, and low (Table 1). The scenarios define the amount of fertiliser applied per area according to the given intensity (int). This scenario-based calculation is made on the basis that the actual mean fertilisation rates using compost and sewage sludge in Germany are unknown. Eq. 5 computes the polluted area $AMP_{f,int,t}$ fertilised with either sewage sludge or compost:

$$AMP_{f,int,t} = \frac{QF_{f,t}}{FINT_{f,int}} \quad , \quad (5)$$

with

$AMP_{f,int,t}$: Area polluted with microplastic from the application of organic fertiliser (f) in scenario (int) in the year (t),

$QF_{f,t}$: Quantity of organic fertiliser as dry solids applied (f) in year (t),

$FINT_{f,int}$: Fertilisation intensity,

int : Fertilisation intensity scenario: high, medium, low.

Table 1 Average quantities of fertiliser dry solids applied per hectare and for different fertilisation intensity scenarios

Fertilisation intensity	Sewage sludge kg/(ha a)	Compost kg/(ha a)
High ^a	1,600	10,000
Medium ^{b)}	600	6700
Low ^{c)}	300	3300

Notes: a) High intensity level for sewage sludge: 5,000 kg/ha within 3 years, i.e., 1,600 kg = 5,000 kg/3years (according to AbfKlärV 2017[39]), high intensity level for compost 30,000 kg/ha in 3 years (according to BioAbfV 2017) [40]. b) Medium fertilisation intensity = High intensity level multiplied by 0.66. c) Low fertilisation intensity = High intensity level multiplied by 0.33.

We make the simple assumption that the same fields have been fertilised with either sewage sludge or compost over time. Eq. 6 computes the average concentration of microplastics per polluted area ($CAMP_{f,int,t}$) on which we expect microplastic emissions from sewage sludge and compost:

$$CAMP_{f,int,t} = \frac{QMPS_{f,t}}{AMP_{f,int,t}} \quad , \quad (6)$$

with

$CAMP_{f,int,t}$: Concentration of microplastic per area for fertiliser (f), intensity (int) and year (t).

We assume that microplastic is homogeneously distributed in the soil due to ploughing, and we define a soil depth of 30 cm as a uniform ploughing horizon all over Germany. We do not consider varying depths of ploughing horizons or the possible transfer of microplastics into deeper soil horizons (e.g., by soil pores or organisms). Based on our assumption that farmers apply bio-solids to light sandy soils, we assume a uniform soil density of 1.2 g/cm³ as the lowest density for light sandy soils. Choosing the lowest soil density of 1.2 g/cm³ results in an overestimation of sandy soils with higher soil density (e.g., at 1.4 g/cm³) (i.e., the worst-case scenario). We present the influence of the soil density value in a separate sensitivity analysis (see Appendix A-4.0). Eq. 7 computes the average mass-based concentration of microplastics in the polluted area soils:

$$CSMP_{f,int,t} = \frac{CAMP_{f,int,t}}{(ha Ap \rho_S)} \quad , \quad (7)$$

with

$CSMP_{f,int,t}$: Concentration of microplastics in the soils for fertiliser (f), intensity (int) and year (t),

ha : One hectare equivalent in square metres = 10,000 m²,

Ap : Ploughing horizon = 0.3 m,

ρ_S : Soil density = 1,200kg/m³.

2.3 Estimating the abatement costs

We calculate the abatement costs for the technologies as the ratio of the costs associated with the technology per ton of fertiliser dry matter, divided by the quantity of abated microplastic per ton of dry matter (Eq. 10). Eq. 8 computes the costs of the abatement technology as the cost of the technical equipment ($TECH_{f,tech}$), the cost of nutrients losses for agricultural production ($NUTR_{f,tech}$) and the CO₂ emission costs ($CO2E_{f,tech}$):

$$CTTE_{f,tech} = TECH_{f,tech} + NUTR_{f,tech} + CO2E_{f,tech} \quad , \quad (8)$$

with

f : sewage sludge, biowaste (as pre-processed compost),

$CTTE_{f,tech}$: Total cost of abatement technology per ton of sewage sludge or biowaste dry matter,

$TECH_{f,tech}$: Cost for abatement technology (e.g., technical equipment) per ton of sewage sludge or biowaste dry matter,

$NUTR_{f,tech}$: Cost of the loss of nutrients available for fertilisation per ton of sewage sludge or biowaste dry matter,

$CO2E_{f,tech}$: Cost of CO₂ emissions at different prices per ton emitted, CO₂eq.

Eq. 9 computes the amount of microplastics abated by considering the quantity of microplastic emitted and applying a reduction factor specific to the abatement technique:

$$QABE_{f,tech} = QMP_{f,t} (1 - REDR_{f,tech}) \quad , \quad (9)$$

with

f : sewage sludge, biowaste (as pre-processed compost),

$tech$: abatement technology (thermal recycling, filter technology for washing machines and plastic detection techniques),

t : time year $t = 2016$,

$QABE_{f,tech}$: Quantity of abated microplastics from fertiliser (sludge, biowaste) per technology and per ton dry matter,

$QMP_{f,t}$: Quantity of microplastics emitted from fertiliser (f) in the year (t),

$REDR_{f,tech}$: Microplastic reduction rate for abatement technologies with corresponding technology performances; thermal recycling = 100%, filter system = 45%, detection system = 80%.

Eq. 10 computes the average abatement costs per quantity of microplastic removed:

$$CABE_{f,tech} = \frac{CTTE_{f,tech}}{QABE_{f,tech}} \quad , \quad (10)$$

with

f : sewage sludge, biowaste (as pre-processed compost),

$tech$: abatement technology (thermal recycling, filter technology for washing machines and plastic detection techniques),

$CABE_{f,tech}$: Abatement costs for fertiliser (biowaste and sludge) and technology per ton matter,

$CTTE_{f,tech}$: Total costs for technology and fertiliser (sludge, biowaste),

$QABE_{f,tech}$: Quantity of abated microplastic from fertiliser (sludge, biowaste) per technology.

2.4 Estimating the abatement effect

We compute the area-based concentrations of microplastics for the different years after implementing the abatement technology by inserting Eq. 9 into Eq. 6 as Eq. 11:

$$CAMP_{f,int,tabat,tech} = \frac{\sum_{tabat_0}^{Tabat} (QMP_{f,tabat} (1 - REDR_{f,tech}))}{AMP_{f,int,tabat}} \quad , \quad (11)$$

with

$tabat_0$: The first year of a simulation period of the abatement scenarios = 2021,

$tabat$: The simulated year of the abatement scenarios = (2022, ..., 2060),

$Tabat$: The last simulated year a simulation period of the abatement scenarios = (2023, ..., 2060),

$QMPS_{f,Tabat} = QMPS_{f,tabat}$: Cumulative quantity of microplastic emitted to soils from fertiliser (sewage sludge, compost) over time for the simulated year with the abatement measure $tabat$.

To compute the mass-based concentration (Eq. 12), we convert the area based concentration by inserting Eq. 11 into Eq. 7:

$$CSMP_{f,int,tabat,tech} = \frac{CAMP_{f,int,tabat,tech}}{(ha \cdot Ap \cdot \rho_s)} \quad , \quad (12)$$

with

$CSMP_{f,int,tabat,tech}$: Concentration of microplastics in the soils for fertiliser (f), intensity (int) and year with implemented abatement measure ($tabat$) as abatement technology ($tech$),

ha : One hectare equivalent in square metres = 10,000 m²,

Ap : Ploughing horizon = 0.3 m,

ρ_s : Soil density = 1,200 kg/m³.

3 Results and discussion

We use the normative emission model described by Eqs. 1 to 7 to estimate the quantities of microplastic released into agricultural soils; to estimate the concentration of accumulated microplastic in agricultural soils, and to estimate the agricultural area potentially polluted by microplastics. We use Eqs. 8 to 12 to assess the efficiency and effectiveness of the abatement measures in reducing microplastic emissions into soils via sewage sludge and compost. We performed the computations using Microsoft EXCEL.

3.1 Microplastics quantities

By computing the quantities of sewage sludge and compost applied to agricultural soils, we estimated the quantities of microplastics emitted. Sectoral statistical data derived from different studies and databases provide the input data for this estimation [41–44]. Figure 1 shows the quantities of sewage sludge and compost applied as organic fertilisers from 1983 to 2016. The annual quantities of sewage sludge applied remain lower than one million tons of dry solids. Prior to 1990, the data excludes the amount of sludge applied in East Germany. However, based on the evolution of the production of sludge quantities in western and eastern Germany [45] it can be assumed that this missing data does not lead to a significant underestimation of the quantities of microplastics before the year 1990.

After reaching a maximum in 1995, the quantity of sewage sludge applied as fertiliser has decreased continuously. The changes in disposal capacities, demand, and sewage sludge use explain this decreasing trend. The phasing-out of sewage sludge disposal in landfill sites expanded the capacities of thermal disposal units (e.g., for incineration)² and therefore created an alternative option for the disposal of sludge [47]. The depletion of phosphorous resources increased the importance of phosphorous recovery and recycling from sewage sludge. Additionally, stricter legislation concerning the agricultural use of sewage sludge and increasing environmental concerns about the presence of pathogens and heavy metals reduced the demand for it as an organic fertiliser and soil amendment. Thus, current legislation prohibits the use of sludge in critical regions (e.g., those close to surface waters or soils with already high levels of pollution).

In Germany, the agricultural use of compost has increased steadily since 1996, driven by the implementation of the Circular Economy Act (the "Kreislaufwirtschaftsgesetz--KrWG" [48]). This law initiated the systematic and wide-scale collection of biowaste from industry and households and the recycling of this biowaste as an organic fertiliser and soil amendment. Since then, the improvement in infrastructures for the collection and recycling of this biowaste has resulted in four times more compost being used in agriculture than is sewage sludge.

²In May 1993 the TAsi (Technische Anleitung Siedlungsabfall) prohibited the disposal of organic waste (such as sewage sludge) in landfills [46].

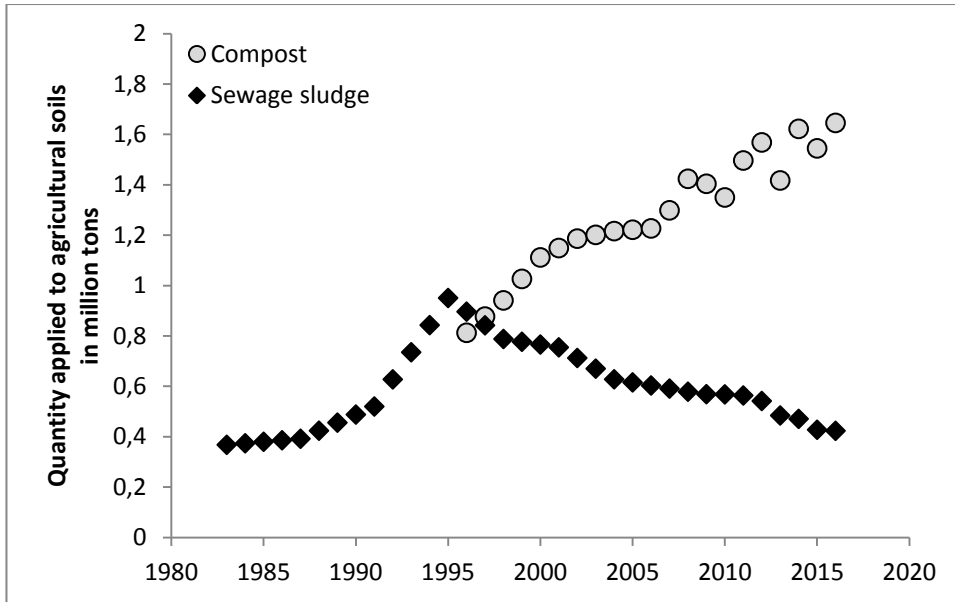


Fig 1 Quantities of sewage sludge and compost dry solids applied to agricultural soils in Germany. Notes: Before the reunification of Germany in 1989, the data is for West Germany only; thereafter, figures for East and West Germany are combined. Source: Own calculations based on [41–44]

Figure 2 presents the annual microplastic emissions from sewage sludge and compost ($QMP_{f,t}$) from 1980 to 2016. The quantities of microplastic emitted from sewage sludge increase over time until 2010, where they remain at approximately 2,500 tons per year between 2011 and 2016. During this period, although the quantities of sewage sludge applied to agricultural soils decrease, the concentration of microplastics in sludge increases, leading to a levelling off phenomenon (see Appendix A-1.0). The total amount of emitted and accumulated microplastics from 1983 to 2016 is approximately 59,000 tons. Of which 49,000 tons is attributed to sewage sludge and 10,000 tons to compost. In 2016, we estimate the concentration of microplastics in sewage sludge ($EF_{sludge,2016} = 0.6\%$) as 15 times higher than in compost ($EF_{compost,2016} = 0.04\%$). Thus, sludge causes five times higher emissions of microplastics although less sludge is used as a fertiliser. It is important to note that the simulated microplastic quantities and subsequent results depend strongly on the assumptions made about the concentrations of microplastics in sludge and compost. We chose the high concentrations provided in the literature under worst-case scenarios, resulting in perhaps an overestimation of the simulated concentrations in soils.

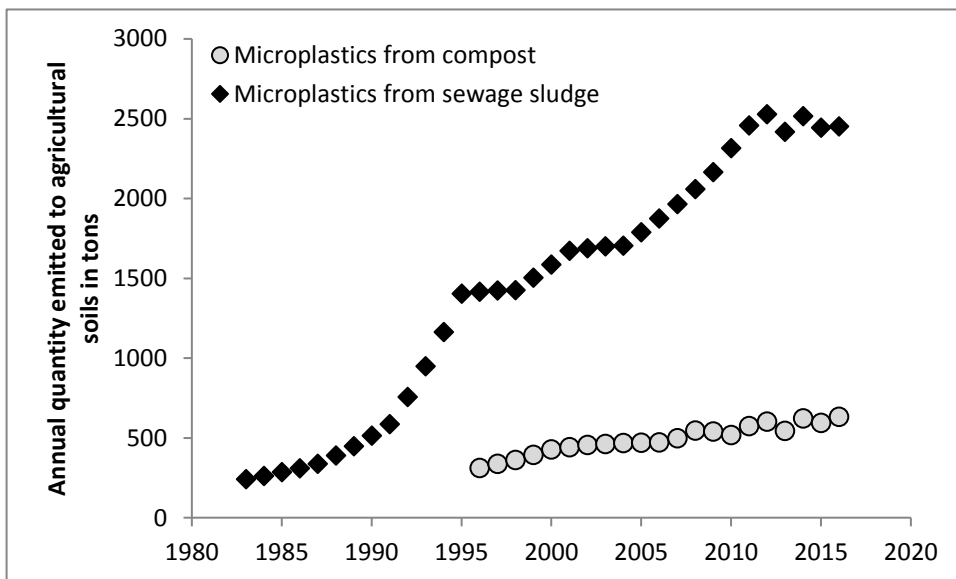


Fig 2 Quantities of microplastic emitted on an annual basis from sewage sludge and compost into agricultural soils in Germany. Source: Own computations based on [41–44]

3.2 Concentration and polluted area

We simulate two worst-case scenarios to estimate the highest concentration of microplastic in agricultural soils and the most significant extent of polluted soils. We simulate both worst-case scenarios for microplastic emissions by sewage sludge and compost with three different fertilisation intensities. Table 2 presents the assumptions of the simulated scenarios. For the worst-case scenario simulating the highest concentrations, we assume that the same fields received sludge or compost during each year of the simulation periods. Thus, microplastic emitted from sludge could have accumulated in these fields between 1983 and 2016 and from compost between 1990 and 2016. The area with the highest concentration is restricted to the area fertilised since the first year, as only this area could have received microplastic from organic fertilisers every year. We select the years between 1983 and 2016 with the largest quantities of applied sludge and compost to determine of the worst-case scenario of the largest polluted area. This quantity determines the area receiving microplastic from the organic fertiliser for at least 1 year. The amount of sludge applied was highest in 1995, while the amount of compost applied was highest in 2016.

Table 2 Soil and fertilisation intensity scenarios

		Unit	Fertilisation intensity		
			High	Medium	Low
Sewage sludge	Application rate	kg / (ha a)	1600	600	300
	Years of application		-----1 or 36 (from 1980 to 2016) -----		
Compost	Application rate	kg / (ha a)	10000	6700	3300
	Years of application		-----1 or 26 (from 1990 to 2016) -----		
Sewage sludge & compost field	Soil density	kg/m ³	----- 1200 -----		
	Ploughing horizon	m	----- 0.3 -----		

Figure 3 shows the simulated microplastic concentrations in the soils and the polluted Utilised Agricultural Area (UAA). For the scenario with the highest fertilisation intensity, we find a cumulative concentration of microplastic of 40 mg/kg (Point A) for the fields receiving an annual sludge application for 33 years, between 1983 and 2016. We expect to find this high concentration on a potentially polluted area of 1.3% of UAA (or 0.22 million hectares). Regarding compost we compute a concentration of approximately 30 mg/kg on 0.5% of UAA (or 0.08 million hectares) (Point D).

The aggregated UAA with the highest concentration of microplastic from sludge or compost accounts for about 1.8% of UAA (or 0.3 million hectares) as the sum of 1.3% of UAA (Point A) and 0.5% of UAA (Point D). For the scenario with the lowest fertilisation intensity, we simulate the maximal extent of polluted UAA with any microplastic present in the soil after at least one application of fertiliser (Points I and L). These fields represent 19% of UAA (or 3.17 million hectares) for sludge and 3% of UAA (or 0.5 million hectares) for compost, with correspondingly marginal microplastic concentrations present. The aggregated UAA with any microplastic originating from sludge or compost present is about 22% of UAA (or 3.67 million hectares). This being the sum of 19% of UAA (Point I, the area fertilised with sludge) and 3% of UAA (Point L, the area fertilised with compost).

In the worst-case scenario of high fertilisation intensity, we assume that farmers apply the maximum quantity of sludge or compost each year. In reality, such a high annual fertilisation intensity may not be practical. For example, after reaching the targeted organic matter content in soils, farmers may reduce the fertilisation rates of both sludge and compost. Thus, the in-vivo concentration and polluted area size may lie between the simulated values for both low and high fertilisation intensities.

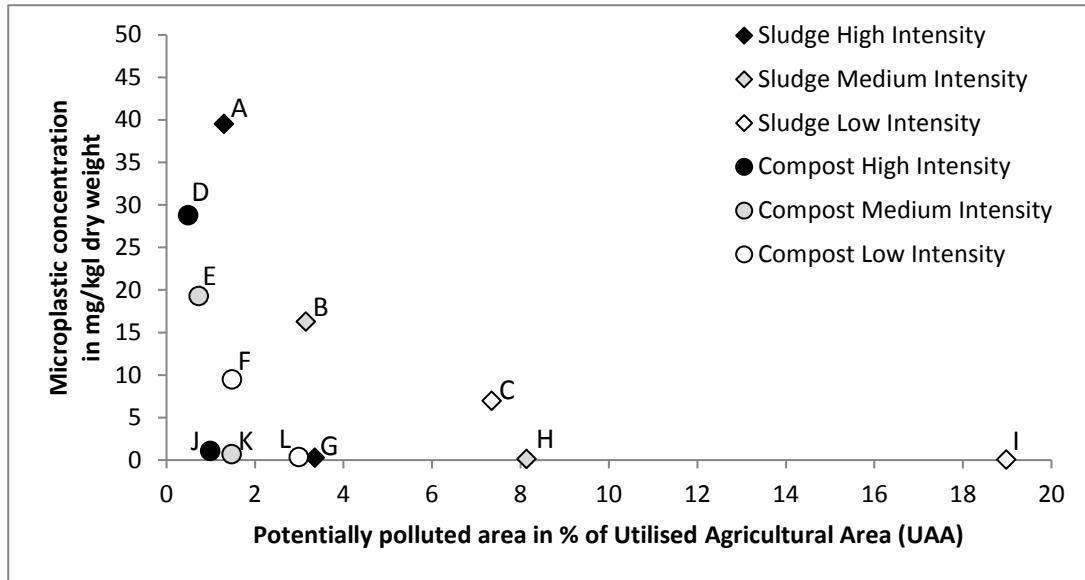


Fig 3 Microplastic concentrations in agricultural soils and the extent of polluted areas for the simulated scenarios of high, medium and low fertilisation intensities for 2016.

Notes: 1 % of UAA (Utilised Agricultural Area) = 0.167 million hectares

The values presented in Figure 3 are benchmark values of microplastic concentrations in soils and potentially polluted areas for the whole of Germany. However, the concentrations and extent of polluted areas can differ at the regional level. Figures 4a to d present the potentially polluted areas at the regional county level for the reference year 2016 for high fertilisation intensities (Figures a and c) and low fertilisation intensities (Figures b and d). The 2016 snapshot illustrates significant regional heterogeneity of potentially polluted areas. Under the high fertilisation scenario with sludge, the potentially polluted soils amount to between 1 and 4% of UAA in the northwestern of Germany, where farmers have traditionally applied more sludge as fertiliser than in the southern regions [49]. In the southern regions, the regional governments recommend not applying sludge as an organic fertiliser [50–52]. Therefore, in Baden-Württemberg in the southeast, the agricultural disposal of sludge as fertiliser has been almost completely abandoned; disposal has shifted to thermal recycling and exportation [51].

In regions close to densely populated urban areas, the extent of polluted agricultural area is high because of the high production and supply of sludge. The low transportation value of sewage sludge restricts the transportation distance from wastewater treatment plants to the application sites. Consequently, the application of sewage sludge as a fertiliser is higher in regions close to large cities such as Hamburg, Hannover and Dortmund in the northern part of the “Ruhrgebiet” (see Figures 4a and b). The regional distribution of areas polluted by microplastic from compost follows a similar pattern and is also due to the same low transportation value of the waste. Polluted areas of between 4 and 6% of UAA can also be found around Frankfurt, Stuttgart and Munich (see Figures 4c and d). Regional analysis suggests that the areas around big cities are likely to be pollution hotspots, and large areas or many sites with potentially polluted soils can be expected. These regions may require particular attention for environmental assessment purposes. Furthermore, relevant fields in these regions may also be of interest for in-situ microplastic sampling and analysis.

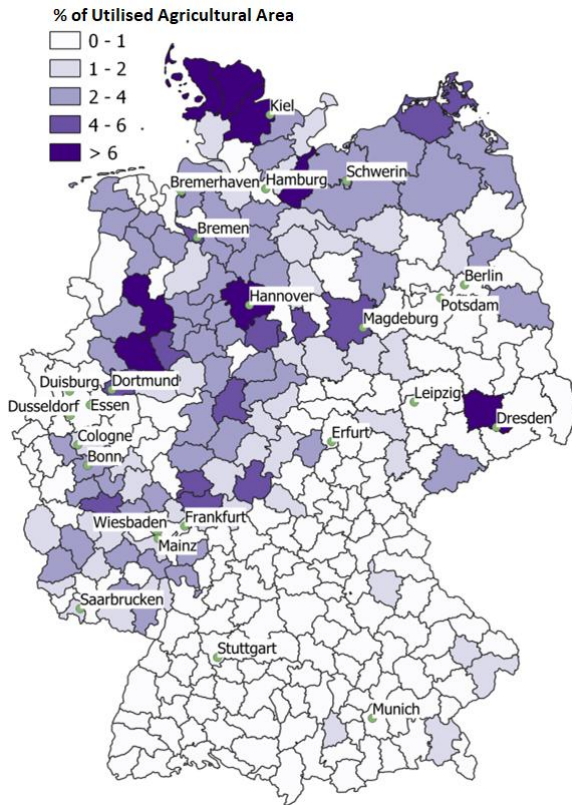


Fig. 4a Area potentially polluted by microplastic from sludge under fertilisation intensity of 1.6 t/ha in the year 2016

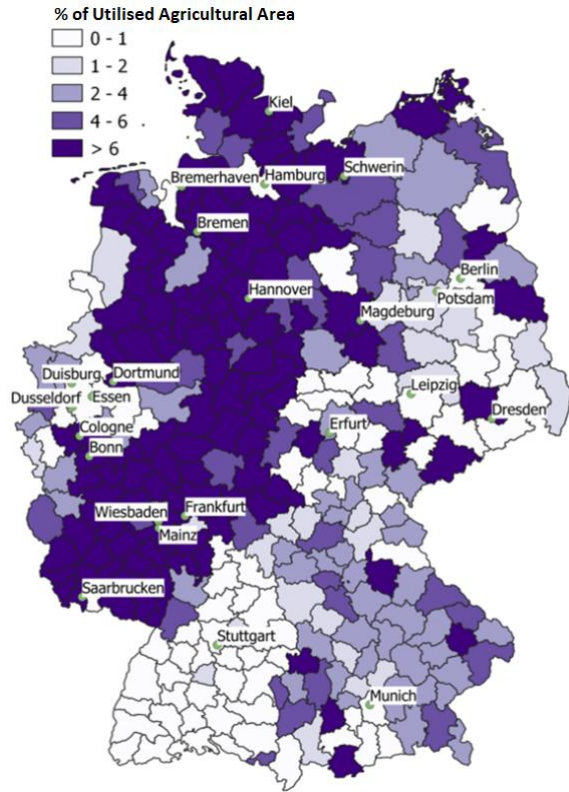


Fig. 4b Area potentially polluted by microplastic from sludge under fertilisation intensity of 0.3 t/ha in the year 2016

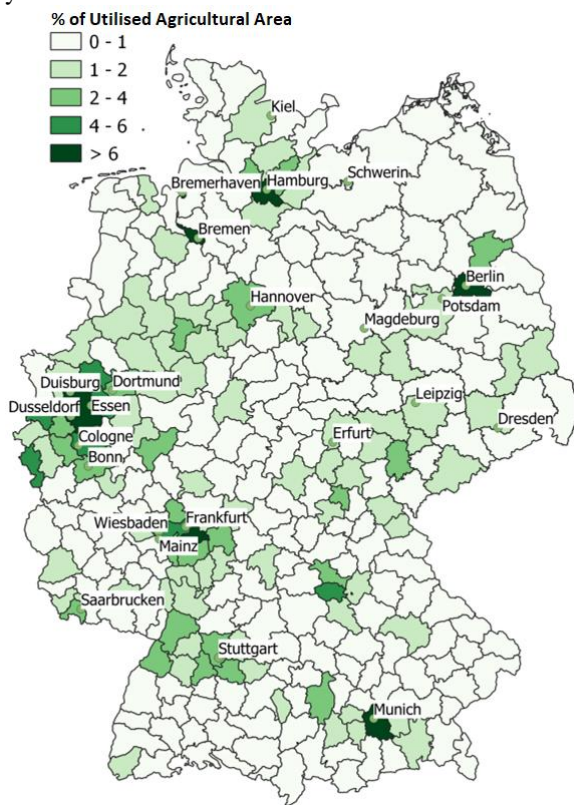


Fig. 4c Area potentially polluted by microplastic from compost under fertilisation intensity of 10 t/ha in the year 2016

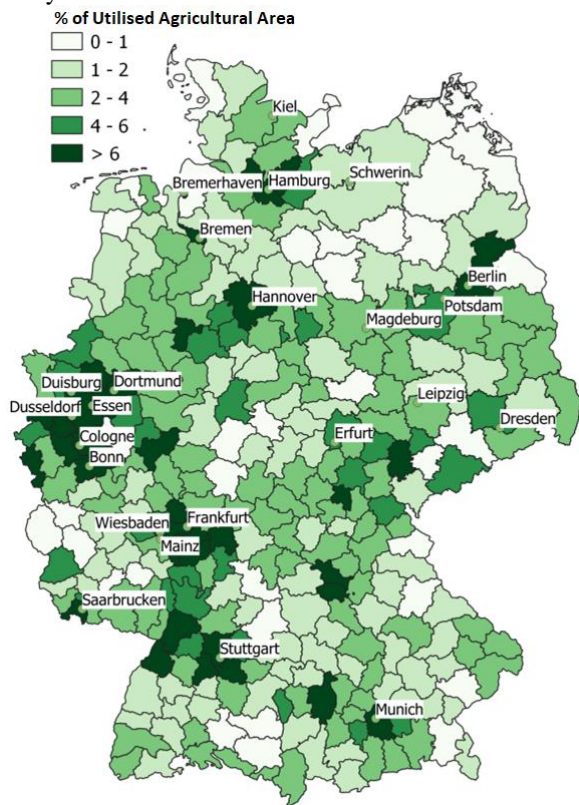


Fig. 4d Area potentially polluted by microplastic from compost under fertilisation intensity of 3.3 t/ha in the year 2016

3.3 Abatement measure scenarios

Regionally, polluted areas with high microplastic concentrations may require measures according to the environmental damage thresholds defined by future research. The establishment of pollution thresholds may be based on both the negative impacts of microplastic in the terrestrial environment and on the potentially negative impacts caused by the loss of microplastics from soils (e.g., transport into aquatic systems caused by soil erosion).-Therefore, knowledge on potential abatement measures may become relevant for environmental research and policy to reduce microplastic emissions from sewage sludge and compost.-In additional simulations, we analyse different abatement measures, such as the installation of filter systems in washing machines and detection systems for the collection of biowaste. These are “source-reduction” measures and follow the “polluter-pays-principle”. Another technique, thermal recycling, represents an “end-of-pipe” approach and generates additional costs for farmers and society. It terminates the land application and availability of these fertilisers for agricultural production and leads to an increase in CO₂ emissions during the incineration process.

First, we compute for the reference year 2016, the relative cost-efficiency and effectiveness of the measures: the average abatement costs and the abatement effect. Then, we compare the results with a reference scenario in which no measures are applied to reduce microplastic emissions. Finally, to evaluate the long term effectiveness of the measures, we simulate the evolution of microplastic concentration in the soils until the year 2060.

3.3.1 “No-Action”-Scenario

The land-based disposal of sludge and compost as organic fertilisers continues without any abatement measures, without reducing microplastic emissions and without additional costs. We assume the microplastic content in sludge remains at the level defined for the reference year 2016. For the long-term simulation until 2060, the application rate of sludge increases by the average change from 2015 to 2020. In Germany, all sludge from wastewater treatment plants with population equivalents of more than 50,000 must, by law, be thermally recycled after 2032. Wastewater treatment plants treating smaller volumes can continue with land-based disposal [53]. Thus, the “No-Action”-Scenario is not realistic and serves only as counter-factual for comparison purposes.

For compost, the “No-Action”-Scenario represents the real situation. Limits and standards currently exist for compost which set the maximum level of non-organic items present (i.e., at 1%, [37]). However, measures and standards are missing to reduce the level of microplastic emissions to agricultural soils. For the long-term simulation, we assume that there will be an improvement in the infrastructure for biowaste collection and allow for the collection of additional biowaste, which was not collected from all households in 2016. Up to 2060, the quantity of biowaste collected will increase at a rate of 1% per year and by 50% in total, compared to 2016. This increase is consistent with the estimate provided by Herrmann et al. [54] on the hidden potential of biowaste [54]. We assume that the microplastic content of the compost remains stable over this time.

3.3.2 “Thermal-recycling”-Scenarios

This scenario roughly represents sludge disposal management in Germany. We simulate that beyond 2030 all wastewater treatment plants will be obliged by law, to dispose of sewage sludge via thermal recycling. For simplicity reasons, we assume that small wastewater treatment plants also thermally recycle their sewage sludge. Regarding compost, we assume that the majority of the microplastics entering compost originate from households and industry and that only this fraction of biowaste is thermally recycled. Biowaste from landscaping (e.g., cuttings) continues to be recycled on land as compost. Thermal recycling reduces microplastic emissions from sludge and compost to soils by 100%. We assume that up to 2016, microplastics accumulate in the soil and remain unchanged without translocation or decomposition. Thus, the concentration of microplastics in the soil in 2016 will remain unchanged in 2060.

To estimate the costs of the thermal recycling of sludge and compost, we consider the technical costs associated with the process. We also consider the cost of the loss of nutrients no longer available for agricultural production and the costs associated with CO₂ emissions resulting from the incineration process. We estimate that the technical cost associated with the thermal recycling of sewage sludge is higher than for compost because of the lower calorific value of sludge. We do not consider the construction costs for thermal recycling plants or other fixed costs, which would further inflate the cost of thermal recycling. To quantify the costs incurred by the loss of soil nutrients, we assume that farmers replace the nutrients lost with mineral fertilisers and the organic matter lost by straw. To derive the cost of the CO₂ emissions, we assume that in land-based recycling techniques, the carbon from the organic matter in sludge and compost will be retained for longer durations in the soil. We simplify the scenario by assuming that land-based recycling techniques result in no greenhouse gas emissions.

In contrast to land-based disposal, during thermal recycling, the incineration of organic matter emits additional CO₂ to the atmosphere, contributing to global warming. We assume that the carbon in biowaste and sludge is transformed entirely into CO₂, and we exclude the emissions of other greenhouse gases such as nitrogen oxides. We then compute the cost of emissions for different carbon price scenarios: 50, 100, and 200 EUR/t CO₂eq.

3.3.3 “Filter-system”-Scenario

This scenario is based on the abatement measure foreseen in France. As the leading European country, France intends to make it compulsory for washing machine manufacturers to equip new machines with filters from January 2025 [55]. This measure would be in line with the European plastic strategy [56] and would help reduce microplastic emissions from households. Under this scenario, we assume that each washing machine in Germany is equipped with a filter to remove textile fibres. To derive the annual costs for the filter systems, we consider the costs of equipping washing machines with filters and for replacing the filter membranes over the 10-year lifespan of a washing machine.

Microplastics in sewage sludge released from textile fibres during the washing of laundry in households and industry accounts for 57% of all microplastics in sludge. The potential reduction in microplastic emissions to sludge by the use of filters is 80%. Thus, the filters reduce the microplastic content in sludge by approximately 45%. To simplify the scenario, we assume that microplastic emissions to wastewater and sludge from other sources are constant. In fact, other sources of microplastic pollution to wastewater streams are decreasing. For example in some EU countries, legislation has already prohibited the use of plastic microbeads in personal care products and detergents (e.g., in the Netherlands, France, Ireland, Sweden, UK and Italy).

3.3.4 “Detection-system”-Scenario

This scenario is based on a detection system and policy measures that were tested in a number of German communities (see Appendix A-3.5.1). Packaging material is the main source of microplastic found in compost. Detection systems in refuse trucks, which collect the biowaste from households and industry, identify and quantify the non-organic material in the collected biowaste. If the detection system indicates excessively high levels of non-organic material in the biowaste, the waste collectors reject the collection and inform households and companies that their biowaste fails to reach the required quality standards. The low-quality biowaste must be disposed of separately with additional service charges. By deploying a detection system and enforcing a monetary incentive, the plastic content of the collected biowaste declines by 90%. To compute the technical costs, we apply the annual cost of the detection system to an estimated number of refuse trucks collecting biowaste. Since statistical data concerning the total number of refuse trucks could not be retrieved, we derive the number of trucks collecting biowaste in Germany. To cover the possibility of having a higher or lower number of trucks than estimated, we compute the costs in a sensitivity analysis for the varied number of these vehicles (see Appendix A-3.5.1).

Table 3 summarises the assumptions of the different scenarios. Appendix A-3.5 presents the detailed assumptions, computations and sources of data and information. Indeed, the data provided gives a rough estimation because the assumptions made for the simulated technologies are based on pioneering techniques. Therefore, the interpretation of the results is limited to ranges and should not be considered as exact figures. The computed abatement costs are only intended as a basis for the ordinal comparison of the different abatement measures rather than for the interpretation of absolute costs. Furthermore, the results require future updating and revision because technological progress might change the assumptions concerning costs, prices and efficiencies.

Table 3 Overview of the reduction rates and costs

Abatement effect	Sewage sludge		Compost/biowaste	
	Thermal recycling	Filter system	Thermal recycling	Detection system
Reduction rate	100%	45%	100%	80%
Costs				
Cost of technique	2.5 EUR/(t dry matter) additional cost compared to landbased application	35 EUR per filter and washing mashine, 0.8 EUR per filter membrane	0.90 EUR/(t dry matter), additional cost compared to landbased application	3965 EUR per refuse truck for biowaste collection per year
Cost of nutrient losses	144 EUR/t		55 EUR/t	
Cost of CO ₂ emissions	assumed from 0, 50, 100, and 200 EUR/t CO ₂ eq		varied from 0, 50, 100, and 200 EUR/t CO ₂ eq	
Projection to 2060				
Quantity of sludge and compost applied to soils	Reduced to zero tons in 2021	An annual application of sludge until 2060 based on the average application rate from 2015 to 2019	Increase of collected biowaste from households by 0.5% annually until 2060	

Notes: Filter systems reduce fibres from textile washing by 80%, which corresponds to a reduction of approximately 45% of the total microplastic load in sewage sludge. Detection systems reduce the quantity of non-organic waste in the biowaste collection container by 80%.

3.3.5 Efficiency and effectiveness

Table 4 presents the average abatement costs and effect of the simulated measures. For sludge, the average abatement costs are significantly higher for the filter system than for thermal recycling process, even when assuming a high carbon price of 200 EUR/t CO₂eq. The filter system achieves a reduction of 1,000 tons per year of microplastics which is less than half of that achieved through the thermal recycling of sludge with 2,500 tons per year. To further reduce the presence of microplastics in wastewater and sludge, additional measures (e.g., technical standards) would be needed to lower emissions from the cleaning of containers (17% of the total microplastic load in sewage sludge), cosmetics and personal care products (14%) and cleaning products (3%). To retain their market share by “greening” their products, some producers of personal care and cleaning products have already considered removing microplastics as an ingredient. As microplastics are publicly regarded as pollutants, consumers favor products without them. In some products, microplastics can be replaced by more environmentally friendly particles to achieve abrasive or covering effects (e.g., natural crystals: salt, sand).

Reducing the remaining microplastics at no cost would reduce the abatement cost associated with filters to only 120 EUR/kg. This value is still however higher than the abatement cost of thermal recycling, simulated with a high carbon price of 200 EUR/t CO₂eq (Table 4). The limited abatement effect (i.e., reduction by 45%) and the high associated costs explain the lower efficiency and effectiveness of the filter system compared to thermal recycling. Furthermore, other aspects, not included in the simulation, would increase the attractiveness of the thermal recycling of sewage sludge. Thermal recycling prevents the emissions of pollutants other than microplastics into the soil and aquatic systems (e.g., antibiotics, heavy metals and pathogens). It also allows for the recovery of phosphorous, which can be used as a mineral fertiliser.

Thus, the results indicate that the German thermal recycling strategy for sludge from wastewater treatment plants serving more than 50,000 population equivalents is cost-efficient and effective compared to the filter system. However, the filter systems could contribute to the reduction of microplastics in regions with lower population densities and smaller wastewater treatment plants, which continue with the land-based disposal of sewage sludge [53]. Abatement using filtration techniques and continuing with the land-based disposal of wastes

are in line with the principles of the European Circular Economy Strategy and with soil and environmental protection [57]. In addition to the removal of microplastics from personal care and cleaning products, and the introduction of technical standards against the emission of microplastics, thermal recycling and the regional use of filtration systems could effectively reduce microplastic emissions from the land-based disposal of sewage sludge.

Table 4 Annual average abatement costs and the abatement effects of the simulated measures for the year 2016

		Sludge	Biowaste used for compost		
			Number of refuse trucks used for biowaste collection		
Assumptions of fitted number of refuse trucks			1400	2500	3000
Filter system for washing machines	[EUR/kg] ^a	264	NA	NA	NA
Detection system for biowaste collection	[EUR/kg] ^a	NA	9	16	19
Thermal recycling of sludge or biowaste, carbon price = 200 EUR/t CO ₂ eq	[EUR/kg] ^a	110	262	262	262
Thermal recycling, carbon price = 100 EUR/t CO ₂ eq	[EUR/kg] ^a	85	164	164	164
Thermal recycling, carbon price = 50 EUR/t CO ₂ eq	[EUR/kg] ^a	73	115	115	115
Thermal recycling, no carbon price	[EUR/kg] ^a	61	66	66	66
Annual abatement effect					
Filter system for washing machines	[tons]	1112	NA	NA	NA
Detection system for biowaste collection	[tons]	NA	612	612	612
Thermal recycling	[tons]	2450	680	680	680

Notes: (a) EUR/kg refers to kg dry weight; NA = not applicable because not computed for this option.

Regarding biowaste, the abatement costs associated with the use of detection systems on refuse trucks are lower than those associated with thermal recycling. This is the case even when comparing the maximum costs (19 EUR/kg) associated with the detection system (i.e., 3,000 trucks) with the lowest costs (66 EUR/kg) for thermal recycling, meaning at zero carbon cost.

The costs associated with the loss of compost nutrients are relatively high (see Appendix A-3.0). Hence, limiting pollution at the source allows nutrients to remain available for agricultural production. As an end-of-pipe solution, thermal recycling does not allow for the direct recovery of nutrients as with land application although phosphorous can be recovered from the incineration residue. Equipping more than 10000 refuse trucks with detection systems would lead to much higher abatement costs than those associated with thermal recycling. Considering the total number of trucks (12,000) collecting biowaste and other wastes in Germany [58], assuming the use of 10,000 refuse trucks for the biowaste collection is unrealistically high. Regarding the abatement effect, the detection system and thermal recycling are comparable in reducing microplastic emissions by 612 and 680 tons, respectively.

3.3.6 Evolution of the microplastic concentration

To analyse the effectiveness of the abatement measures over time, we simulate the concentrations over the period 2016 to 2060. For this long simulation period, we make strong *ceteris paribus* assumptions concerning the simulated fertilisation intensity and exclude potential changes to environmental policies and technological progress (e.g., development of biodegradable (bio) plastics and textiles with lower fibre emissions). Figure 5 displays the evolution of the concentration over time under the worst-case scenario of the highest fertilisation intensity with high microplastic emissions. Under the No-Action scenario, the microplastic concentration in soil from sludge will reach about 50 mg/kg dry weight in 2020 and 160 mg/kg dry weight by 2060. With filter systems in place in 2021, the concentration would reach 110 mg/kg dry weight in 2060. With thermal recycling of sludge, the concentration would remain below 60 mg/kg dry weight in 2060. The microplastic concentration from compost without abatement would reach about 30 mg/kg dry weight in 2020 and approximately 75 mg/kg dry weight in 2060. By applying detection systems or the use of thermal recycling processes on biowaste (com-

post), the microplastic concentration increases at a low rate to less than 40 mg/kg dry weight in 2060. Over the long term it can be said that the effectiveness of the detection system is comparable to that of thermal recycling.

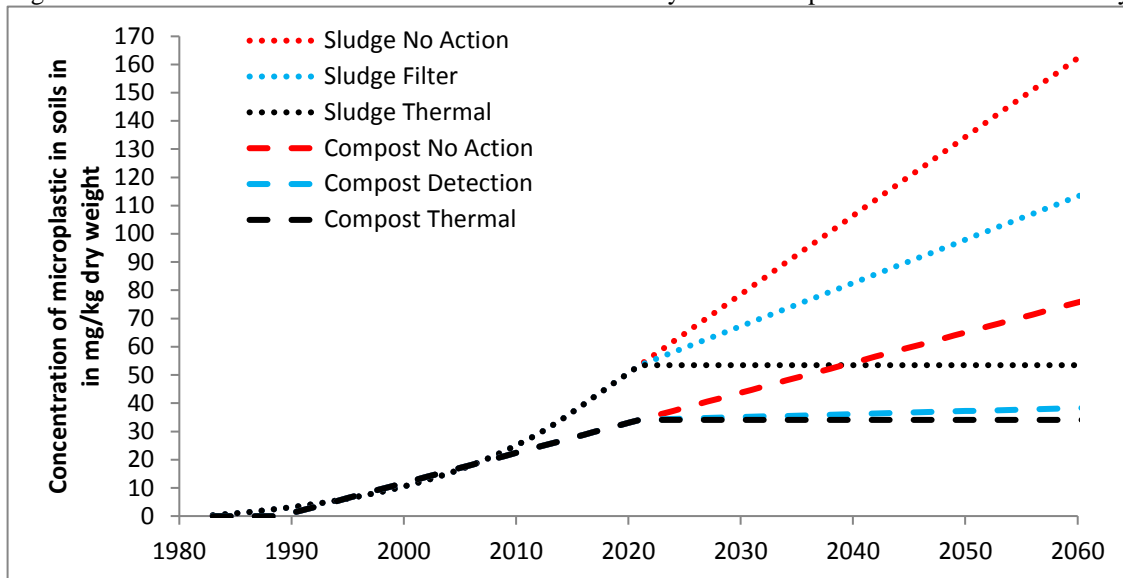


Fig. 5. Effectiveness of simulated abatement measures in the long term

Note: in the scenarios "Compost Thermal" and "Compost Detection", we refer to the thermal recycling of biowaste and the detection system applied to the collection of biowaste.

4 Conclusions

Under worst-case scenarios, the pollution levels simulated with the normative emission model indicate that the present expected microplastic concentration in soil from sludge or compost should not exceed concentrations of between 40 and 50 mg/kg. The polluted area with such a high concentration, would, however, cover approximately 2% of Utilised Agricultural Area (UAA) (or 0.3 million hectares) in Germany. These areas are expected to be located close to the bigger cities. The area potentially affected by pollution from at least one single sewage sludge or compost application accounts for about 22% of UAA (or 3.7 million hectares). However, the concentrations of microplastic in the soils in this extended area are likely to be marginal. The continued application of sewage sludge and compost on lands over the next 40 years with high fertilisation intensities, but without abatement measures, could result in the presence of high microplastic concentrations in the soils of more than 150 mg/kg dry weight and 70 mg/kg dry weight respectively. As an end-of-pipe solution for sewage sludge, thermal recycling is a more efficient and effective abatement measure than the filter systems in washing machines, which is a source-reduction technique. Whereas for compost, the use of detection systems as a source-reduction measure is an efficient abatement measure and comparable in terms of abatement effect to thermal recycling as an end-of-pipe solution.

The constraints of the method used and the scope of the research question have set the limits of this study. The results reflect the defined scenarios in which the ranges were varied for the pollution scenarios. Measured in-vivo, the conditions (e.g., soil density) might vary somewhat from the model assumptions and result in different microplastic concentrations being determined than those simulated. The model builds upon the currently available technical and environmental and information. New technical and research developments may require the model to be updated and revised. Thus, the preliminary results serve as a starting point for discussions and are subject to further revisions. Additionally, given that the normative simulation model represents an ideal situation with many *ceteris paribus* assumptions, analytical evidence is required to calibrate and validate the simulation model.

Simulation of future microplastic pollution concentrations indicates that the lack of action could result in high microplastic concentrations in soils in the medium to long term. This finding calls for the adoption of environmental policies to help preserve, protect and improve the quality of soils. The tackling of the progressive pollution of soils with microplastic is in line with the European Green Deal initiatives [59]. This aims to reduce soil pollution as a means of protecting the terrestrial ecosystem and maintaining soil productivity as outlined in the European Union Action Plan on "Zero Pollution" [57] and the European "New Soil Strategy" [60]. Furthermore, evaluating potential pollution and abatement measures provide scientific and technical data required for environmental policy decision-making [56].

As mentioned earlier, thermal recycling of sewage sludge is more effective and efficient than the use of washing machine filters. This confirms that the German environmental strategy for thermal sewage sludge management, which is implemented until 2032 for the larger treatment plants [53] provides a better alternative than a source-reduction strategy such as the use of washing machine filters. However, for regions with smaller treatment plants where land-based sludge disposal continues, filter systems for washing machines may provide an opportunity to reduce microplastic pollution of soils. Furthermore, the use of detection systems for the collection of biowaste is more cost efficient and as effective as the thermal treatment of biowaste. Additionally, reducing plastic pollution at the source in biowaste is in line with the objectives of the European Union Circular Economy Strategy [57].

This paper provides a partial analysis of soil pollution with microplastics, focusing on the agricultural application of sewage sludge and compost. The concise assessment of soil pollution with microplastics requires further research on all relevant sources that may enter the soils (e.g., tyre abrasive from roads) and the economic agents along the pollution chain (e.g., society, industry, farmers) [13]. Thus, understanding the complexity of microplastic pollution requires holistic evaluation approaches, as is the case for many other environmental problems [61, 62]. The application of normative models is a complementary approach to the methods used in analytical science. Interdisciplinary collaboration between modelling research and analytical science is a fruitful way to bridge the knowledge gaps concerning microplastics. Model simulations estimate pollutant concentrations, assess polluted areas and identify interesting sites for in-situ sampling. Analytical science generates measured data for the calibration, validation, and revision of the models. Modelling research as a complementary approach to analytical science will contribute to assessing the new environmental problem linked to the still unknown but already ubiquitous pollutant in agricultural soils: microplastics.

Statements & Declarations

Authors' contributions

Martin Henseler: Conceptualisation, data curation, formal analysis, methodology, software, validation, visualisation, writing - original draft. Micheal B. Gallagher: Writing - review & editing. Peter Kreins: Funding acquisition, project administration.

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