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

3
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5

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12 **Abstract**

13 Microplastic pollution in soils is a recent challenge for environmental science and policy.
14 Designing and implementing policies to mitigate microplastic emissions requires scientific
15 data, which is rare because analytical methods to detect and quantify microplastics in soils are
16 still under development. Using a normative emission model we simulate for the year 2020 a
17 microplastic concentration in agricultural soil between 40 and 50 mg/kg, which we expect to
18 find on 2% of Germany's utilized agricultural area. On around 20% of utilized agricultural
19 area, we expect any microplastic pollution present from sludge or microplastic. At the region-
20 al scale, we expect the difference of pollution between sites to be close to urban regions and
21 less urban regions. We find that for sludge, thermal recycling (end-of-the-pipe treatment)
22 reduces the microplastic emissions more cost-efficiently and effectively than filtering the
23 microplastic emissions from the waste-water. For compost, the application of detection sys-
24 tems and quality control for the biowaste collection (source of pollution) is a more cost-
25 efficient abatement measure than thermal recycling. This approach is of comparable effec-
26 tiveness to thermal recycling. The presented results must be updated with future research re-
27 sults. But these model results can contribute to research on reducing microplastic pollution in
28 agricultural soils.

29 **Key words:** environmental assessment, normative model, abatement cost, efficiency, effec-
30 tiveness
31

32 1 Introduction

33 Microplastic pollution is a recent challenge for environmental science and policy.
34 Microplastics, commonly defined as solid plastic particles of the size between 1 and 5000 μm ,
35 have been found in nearly all environmental systems (e.g., Gestoso et al. 2019, Horton et al.
36 2017, Koelmans et al. 2017). Many industrial and household sources emit different quantities
37 of microplastics into atmosphere or into aquatic or terrestrial ecosystems. A lack of
38 knowledge on the bio-physical behavior of microplastics in ecosystems and on their impacts
39 on living organisms is of increasing concern to society and researchers.

40 Insufficient empirical data on the emission quantities, on the impacts and on potential abate-
41 ment measures has made microplastic pollution a threatening environmental problem at a
42 global and European level. Society perceives microplastic as a threat and demands action for
43 environmental and human health protection.

44 In its principles of precaution and prevention, European environmental policy legislation fo-
45 cuses on “preserving, protecting and improving the quality of the environment” and “protect-
46 ing human health” (European Union 2012). Recently, these objectives were also emphasized
47 for soil pollution in the EU Action Plan on “Zero Pollution” (European Union 2020a) and the
48 European “New Soil Strategy” (European Union 2021). Both strategies are part of the Euro-
49 pean Green Deal (European Commission 2019) aiming at the reduction of soil pollution to
50 protect and improve the terrestrial ecosystem and aquatic ecosystem, retain soil productivity
51 and protect human health.

52 Environmental policy design should ideally target the source of microplastic pollution and
53 obligate associated costs to be paid by the polluter. However, European environmental policy
54 principles also require an evaluation of potential benefits and costs of action or lack of action
55 and an assessment of costs in terms of proportionateness. Available scientific and technical
56 data are to serve as the basis for evaluation and policy design (European Union 2012). Thus,
57 the current lack of knowledge on the status, the processes and the impacts of microplastic
58 pollution, makes it difficult or impossible to legislate environmental policy against
59 microplastic pollution in the different ecosystems.

60 The potential environmental threat of microplastic pollution in terrestrial ecosystems has re-
61 cently gained increased attention (e.g., Hurley and Nizzetto 2018, de Souza Machado et al.
62 2018, Rillig et al. 2017, Nizzetto et al. 2016). Microplastics were found in agricultural soils
63 as textile fibers originating from sewage sludge as early as 2005 (Zubris and Richards 2005,
64 Selonen et al. 2020).

65 Microplastics are suspected to have negative impacts on soils ecosystems. They can change
66 physical characteristics of soils (Rillig et al. 2017, Lehmann et al. 2019) and release associat-
67 ed toxic chemicals (e.g., additives, cf. Hahladakis et al. 2018). They can also act as vectors
68 for environmental contaminants like pesticides, heavy metals or antibiotics (Shi et al. 2020).
69 Furthermore, microplastic particles can be ingested by soil organisms. At the nano-scale size,
70 microplastics may even cross biological barriers (Wang et al. 2019, Ng et al. 2018, Koelmans
71 et al. 2017). However, scientific evidence to support these theories on the impacts in ecosys-
72 tems is currently lacking for in situ conditions. Thus, in the natural environment, the toxic
73 concentrations or transportation processes cannot be quantitatively described.

74 The high stability of plastic as a material means that the decomposition (degradation) of
75 microplastic particles under environmental conditions is extremely slow. Thus, researchers
76 expect an accumulation of microplastic in environmental systems (e.g., in soil and water)
77 (Horton et al. 2017). It is assumed that microplastics can be emitted from soils to water sys-
78 tems, where they can have negative impacts on aquatic ecosystems (Horton et al. 2017, Lush-

79 er et al. 2017, Eerkes-Medrano et al. 2015, Bakir et al. 2014). Groundwater flow and soil ero-
80 sion (wind, water) can transport microplastics, and soils with high microplastic content are
81 potential sources for microplastic emissions to other environmental systems such as surface
82 waters. Thus, microplastic-polluted soils as a potential source of emissions to aquatic systems
83 are of interest for research.

84 In agricultural production the land based application of sewage sludge and compost as organ-
85 ic fertilizers are considered as important pathways of microplastic to agricultural soils (Hur-
86 ley and Nizzetto 2018, Ng et al. 2018). Microplastics in sewage sludge and compost are emit-
87 ted by private households and different industries. Microplastics enter wastewater from
88 households and industry (e.g., cleaning products, fibers from synthetic textiles). Sewage
89 sludge, as a residue from the water treatment process, contains these microplastics (Corradini
90 et al. 2019, Kay et al. 2018, Wijesekara et al. 2018). Microplastics in compost originate from
91 private households, industry and landscaping when plastic materials (e.g., food packaging,
92 littered plastic in landscaping clippings) are not (sufficiently) separated from the organic
93 waste before collection and composting. The compost producer can only remove plastic par-
94 ticles down to a certain size, meaning that the separation process is not efficient in removing
95 the smaller plastic fragments (e.g., small thin fragments of plastic film from food packaging).
96 Mechanical processes (e.g., shredding and mixing) degenerate the macro plastic fragment to
97 microplastic sized particles (Bläsing and Amelung 2018, Weithmann et al. 2018).

98 In Germany, a European study area with regionally intensive agricultural production, farmers
99 apply sewage sludge and compost as soil amendments to improve soil structure and as organ-
100 ic fertilizers to supply the soil with nutrients. At the same time, farmers provide German soci-
101 ety with a waste disposal service. But farmers emit microplastics into agricultural soils by
102 spreading sewage sludge and compost on their fields. Microplastics can thus potentially be
103 included in the list of agricultural pollutants (Henseler et al. 2020).

104 However, the lack of scientific knowledge to date does not allow for the development of poli-
105 cies to reduce the suspected pollution of agricultural soils with microplastics (Brodhagen et
106 al. 2017). Gaps in research exist with regard to sources, processes, fates, sinks, exports and
107 impacts of microplastics. (Rillig et al. 2019, Büks et al. 2020). Furthermore, microplastics
108 exist in soils in relatively low concentrations and are difficult to separate from the soil parti-
109 cles. From an analytical point of view, difficulties exist in developing methods to measure
110 microplastics in soils and to carry out impact assessments (Möller et al. 2020, Brennholt et al.
111 2018, Wagner et al. 2014).

112 An increasing number of studies address the problem of microplastic pollution in soils. Most
113 of these studies are review studies and only a few studies provide original empirical findings.
114 While economic literature addresses the problem of the plastic crises (e.g., Batker 2020) and
115 plastic pollution in marine environment (Abate et al. 2020) economic studies on microplastic
116 pollution in terrestrial systems are still rare and they tend to be of qualitative nature. For ex-
117 ample, Henseler et al. (2020) describe the microplastic pollution of agricultural soils as a new
118 challenge for agricultural and environmental policies and discuss if agriculture, which is
119 providing the service of bio-waste disposal to the society should be considered pollutant or as
120 a victim of microplastic pollution (Henseler et al. 2020).

121 The present study contributes to the environmental economic literature by providing quantita-
122 tive empirical findings on microplastics in agricultural soils. Concretely, the study addresses
123 the following goals and objectives: (i) to present a normative emission model at the sector
124 level on microplastic emissions from sludge and compost into agricultural soils; (ii) to simu-
125 late emission scenarios in order to estimate the concentration of microplastic in soils and the
126 area with polluted soils; (iii) to evaluate potential abatement measures with respect to their

127 cost-efficiency and effectiveness. Finally the results of this study can (iv) contribute to the
128 discussion on microplastic pollution.

129 **2 Model and data**

130 We developed a normative emission model for Germany to estimate the quantities of
131 microplastic released from sewage sludge and compost and the concentration of microplastic
132 accumulated in agricultural soils. The data to be used in the model and the assumptions are
133 derived from literature and statistics.

134 **2.1 Estimating the concentration of microplastic in sewage sludge and compost**

135 We use research by Bertling et al. (2018) and Kehres (2019) on microplastic concentrations
136 in sewage sludge and compost to estimate the released quantities of microplastic We assume
137 that the estimated microplastic concentrations are representative of the average national con-
138 centrations in Germany.

139 **2.1.1 Concentration of microplastic in sewage sludge**

140 A few analytical studies have been published concerning the microplastic content of sewage
141 sludge. We use the mass based emission quantities published by Bertling et al. (2018) for the
142 whole of Germany by aggregating all sources relevant to wastewater and sewage sludge: tex-
143 tiles, cosmetics, cleaning and personal care products.

144 Equation 1 describes the calculation of microplastics in sewage sludge from the selected
145 sources for 2016, which we define as the reference year. We consider the filtration rate for
146 microplastics in wastewater treatment plants to be 95%. The empirical filtering rate is as-
147 sumed to be between 95 and 99% (Bertling et al. 2018). Thus, we assume the “worst case”
148 scenario for the effectiveness of filtration. This means that 5% of microplastics will leave the
149 treatment plant with the treated waste water into aquatic systems, while 95% will remain in
150 the sludge. We compute an average microplastic content in sludge of 0.6% dry weight for the
151 reference year 2016.

152 Literature cites smaller microplastic concentrations reaching from mean values of 0.05% to
153 0.1% dry weight (Crossmann et al. 2020) to 0.4% dry weight (Okoffo et al. 2020). We follow
154 the worst-case assumption by selecting 0.6% as a higher concentration representative for
155 Germany.

$$156 \quad MP_{CONC}_{sludge} = \left(\frac{\sum_{source} MP_{EM}_{source} * POP_{2016}}{Q_{sludge,2016}} \right) * FR \quad (\text{Eq. 1})$$

156 With

157 MP_{CONC}_{sludge} = concentration of microplastics in sewage sludge as % dry weight

158 MP_{EM}_{source} : annual emissions of microplastics per capita in 2016 expressed as g/(head *
159 year): Textile fibers from households and industry = 76.8 g/(head*year) (57.7%); Industri-
160 al cleaning = 23 g/(head*year) (17.0%), Cosmetics = 19 g/(head*year) (14.0%), Abrasives
161 in pipes = 12 g/(head*year) (8.9%), cleaning products and personal care products = 4.6
162 g/(head*year) (3.4%) computations based on Bertling et al. (2018).

163 POP_{2016} : population in Germany in 2016 = 82.3 M

164 $Q_{sludge,2016}$: quantity of sewage sludge produced in 2016 in g

165 FR : filtration rate = 95%

166 The amount of microplastic in wastewater is determined by the emissions from various
167 household and industrial sources. Thus, we assume that the amount of microplastics in

168 wastewater and sewage sludge has changed over the period from 1983 to 2016. We use the
 169 global development of polyester production as an index to consider the changes in the con-
 170 centration of microplastics over time. Since synthetic fibres are the main source of microplas-
 171 tics in sludge, we use this index as the basis for all calculations of microplastic concentrations
 172 in wastewater and sewage sludge (for further details, see Appendix).

173 **2.1.2 Concentration of microplastic in compost**

174 Few empirical studies analyze the concentration of microplastics in compost. In composts of
 175 different types, Weithmann et al. (2018) found particle numbers ranging from 14 to 895
 176 items/kg dry weight in the size range of between 1 and 5mm. Bläsing and Amelung (2018)
 177 measured a concentration of microplastics in compost samples ranging from 2.38 mg/kg to
 178 180 mg/kg dry weight, in the size range of between 1 and 5mm, translating into a mean value
 179 of 0.008% dry weight. For this study, we consider the concentration of microplastics in com-
 180 post to be that determined by Kehres (2019) in different types of compost. Kehres (2019)
 181 determines the concentration of plastic particles which are larger than 2mm to be 0.032% dry
 182 weight in certified composts. Kehres (2019) estimates that there is about 10% more plastic
 183 present when considering the size fraction range of 1 - 2mm (Kehres 2019, BGK 2018).
 184 Thus, we derive a concentration of microplastic in compost to be 0.04% dry weight¹ for the
 185 particle size range of 1 to 5mm. Following the worst-case assumption, we select the higher
 186 concentration of 0.04% dry weight as representative for Germany.

187 **2.1.3 Development of the concentration of microplastic in sewage sludge and compost**

188 Equation 2 computes the emission factors ($EF_{f,t}$) for the organic fertilizer (f) in year (t). We
 189 assume that only the emission factor of sewage sludge ($EF_{sludge,t}$) varies over time from 1983
 190 to 1990. Due to missing information on the development of the plastic content in bio-waste,
 191 we assume that the emission factor for compost ($EF_{compost,t}$) is constant over time.

$$192 \quad EF_{f,t} = MPCONC_f * DEV_{f,t} \quad (\text{Eq. 2})$$

192 with

193 $EF_{f,t}$: Emission factor for the organic fertilizer (f) for the year (t).

194 $MPCONC_f$: Concentration of microplastic in the organic fertilizer, sewage sludge = 0.6%
 195 dry weight matter, compost = 0.04% dry weight.

196 $DEV_{sludge,t}$ = Scaling factor applied the 2016 microplastic concentration in sewage sludge
 197 according to Fig 1

198 $DEV_{compost} = 1$

199 **2.2 Estimating the emissions of microplastic from sewage sludge and compost in agricul-** 200 **ture**

201 To estimate the quantities of microplastics released from sewage sludge and compost to agri-
 202 cultural soils, we develop a normative emission model at the sector scale. The model takes
 203 exclusively sewage sludge and compost into account and does not consider the other sources
 204 of microplastics. The model (Eq. 3 to 7) simulates the emissions of microplastics as they
 205 should be according to current legislation, for each single year and only for sewage sludge
 206 and compost. The model is therefore a partial normative emission model.

¹i.e., $0.032\% + 10\% * 0.032\% = 0.035\%$ ca. 0.04%

207 Equation 3 computes the quantity of microplastic emitted for the year t and from fertilizer f
 208 (sewage sludge or compost). The sector emission factor $EF_{f,t}$ expresses the concentration of
 209 microplastic in the fertilizer, with $EF_{\text{sludge},t}$ increasing from the year 1983 to 2016 to 0.6% of
 210 dry weight in 2016 (Figure 1) and with $EF_{\text{compost},t}$ as a constant concentration from 1990 to
 211 2016 at 0.04% of dry weight.

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

212 with

213 $QMP_{f,t}$: Quantity of microplastics emitted from fertilizer (f) in the year (t) in mg

214 $QF_{f,t}$: Quantity of fertilizer used (f) in year (t) in tons of dry solids

215 $EF_{f,t}$: Emission Factor for microplastic emissions from fertilizer (f) in year (t) in mg/t

216 f : Fertilizer used; either sewage sludge or compost

217 $t = (1983 \dots 2016)$: The simulated year.

218 Equation 4 describes the cumulated quantities of microplastics released into the soils in the
 219 simulated year t by summing up the quantities of microplastics over the past years. We as-
 220 sume that microplastics emitted from sewage sludge and compost accumulate in the soil over
 221 time. Due to the lack of information on processes, we exclude any metabolisation of
 222 microplastics and presume no losses occur through wind and water erosion.

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

223 With

224 t_0 : The first year, for sludge = 1983, for compost = 1996

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

226 T : The last simulated year = (1984, ..., 2016):

227 $QMPS_{f,T} = QMPS_{f,t}$: Cumulative quantity of microplastic emitted to soils from fertilizer f
 228 (sewage sludge, compost) over time in the simulated year t

229 Based on normative assumptions of the maximal application of fertilizer f , we define three
 230 fertilization intensity scenarios: high, medium, and low (Table 1). The scenarios define the
 231 amount of fertilizer applied per area according to the given intensity (int).

232 Equation 5 computes the polluted area $AMP_{f,int,t}$ fertilized with either sewage sludge or com-
 233 post. This scenario-driven calculation is based on the fact that the actual mean fertilization
 234 rates using compost and sewage sludge in Germany are unknown.

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

235 with

236 $AMP_{f,int,t}$: Area polluted with microplastic from the application of organic fertilizer (f) in
 237 scenario (int) in year (t) in ha

238 $QF_{f,t}$: Quantity of organic fertilizer applied (f) in year (t) in kg of dry solids

239 $FINT_{f,int}$: Fertilization intensity in kg/ha
 240 *int*: Fertilization intensity scenario: high, medium, low

241 **Table 1: Average quantities of fertilizer dry solids applied per hectare and for different**
 242 **fertilization intensity scenarios**

Fertilization intensity	Sewage sludge kg/(ha * a)	Compost kg/(ha * a)
High ^a	1,600	10,000
Medium ^b	600	6,700
Low ^c	300	3,300

243 a) High intensity level: Sewage sludge: according to AbfKlärV2017):(5,000 kg/ha within 3 years, i.e., 1,600 kg = 5,000kg/3years (according
 244 to AbfKlärV 2017), according to DVO compost 30,000kg/ha in 3 years (according to BioAbfV 2017). B) Medium fertilization intensity =
 245 High intensity level * 0.66. c) Low fertilization intensity = High intensity level * 0.33

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

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

250 *with*

251 $CAMP_{f,int,t}$: Concentration of microplastic per area for fertilizer (*f*), intensity (*int*) and year
 252 (*t*) in mg/ha

253 Equation 7 computes the average mass-based concentration of microplastics in the soil of the
 254 polluted area. We assume that microplastic is homogenously distributed in the soil due to
 255 ploughing, and we define a soil depth of 30 cm as a uniform ploughing horizon all over Ger-
 256 many. We do not consider varying depths of ploughing horizons or the possible transfer of
 257 microplastics into deeper soil horizons (e.g., by soil pores or organisms). Based on our as-
 258 sumption that farmers apply bio-solids to light sandy soils, we assume a uniform soil density
 259 of 1.2 g/cm³ as smallest density for sandy light soils. The choosing the very small density of
 260 1.2 g/cm³ results in an overestimation of sandy soils which have higher soil density (e.g., at
 261 1.4 g/cm³), (i.e., the worst case assumption). We present the influence of the value of soil
 262 density in a separate sensitivity analysis (see Appendix A-4.0).

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

263 *with*

264 $CSMP_{f,int,t}$: Concentration of microplastics in the soils for fertilizer (*f*), intensity (*int*) and
 265 year (*t*) in mg/ha

266 *ha*: One hectare equivalent in square meters = 10,000m²

267 *Ap*: Ploughing horizon = 0.3m

268 ρ_S : Soil density = 1.200 kg/m³

269 3 Results and discussion

270 We use the normative emission model described by Equations (1) to (7) to estimate the quan-
 271 tities of microplastic released into agricultural soils; to estimate the concentration of

272 microplastic accumulated in agricultural soils, and to estimate the agricultural area potentially
273 polluted by microplastics.

274 **3.1 The quantities of microplastics released to agricultural soils**

275 First, we estimate the quantities of sewage sludge and compost applied to agricultural soils to
276 derive the quantities of microplastics emitted. The input data for this estimation is based on
277 sectoral statistical data provided by different sources².

278 Figure 1 shows the quantities of sewage sludge and compost applied as an organic fertilizer
279 during the period 1983 to 2016. The annual quantities of sewage sludge applied remain lower
280 than one million tons (dry solids). Before 1990, the data does not include the sludge quanti-
281 ties applied in East Germany. Based on the development of sludge quantities in western and
282 eastern Germany (Gallenkemper and Dohmann 1994), it can be assumed, however, that this
283 missing data from East Germany does not result in a significant underestimation of the quan-
284 tities of microplastics before 1990.

285 The year 1995 saw a peak in the amount of sewage sludge applied and used as fertilizer on
286 agricultural land, the use has dropped off continuously since then. Changes in disposal capac-
287 ities and in the demand and use of sewage sludge explain this decreasing trend. The phasing-
288 out of sewage sludge disposal in landfill sites expanded the capacities of thermal disposal
289 units (e.g., for incineration)³ and thus created an alternative option for the disposal of sludge
290 (Franck and Schröder 2015). The depletion of phosphorous resources increased the demand
291 for sewage sludge as a raw material to recover and recycle phosphorous. Additionally, stricter
292 legislation concerning the agricultural use of sewage sludge and increasing environmental
293 concerns (e.g., due to the presence of pathogens and heavy metals) reduced the demand for
294 sewage sludge as an organic fertilizer and soil amendment. Thus, legislation prohibits the use
295 of sludge in critical regions (e.g., those close to surface waters or soils with already high lev-
296 els of pollution).

297 In Germany, the agricultural use of compost has increased steadily since 1996, driven by the
298 implementation of the Circular Economy legislation (The “Kreislaufwirtschaftsgesetz”,
299 KrWG 2012). This law initiated the systematic and wide-scale collection of biowaste from
300 industry and households, and the recycling of this waste as an organic fertilizer and soil
301 amendment. Since then, the improvement in infrastructures for collecting and recycling bio-
302 waste has resulted in four times more compost than sewage sludge being used in agriculture.

²UBA (2020), BMEL (2019), Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 "Statistik" (2014, 2015).

³In May 1993 the TASI (Technische Anleitung Siedlungsabfall) prohibited the disposal of organic waste (such as sewage sludge) in landfills (TASI 1993).

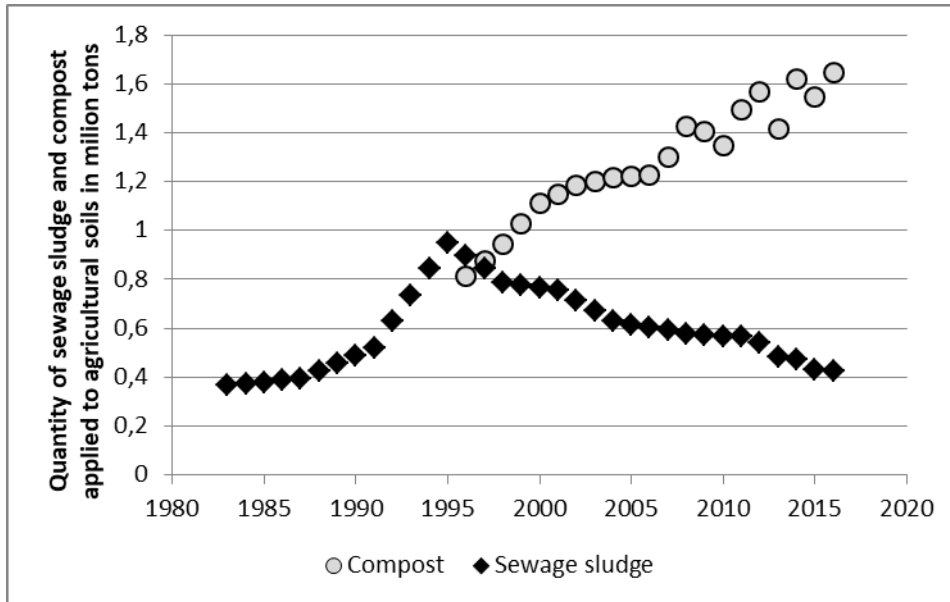


Figure 1. Quantities of sewage sludge and compost dry solids applied to agricultural soils in Germany. Note: before the German reunification in 1989 data represent quantities only in West Germany, after 1989 quantities from East and West Germany are aggregated. Source: Own calculations based on UBA (2020), Bioabfälle, BMEL (2019), Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 "Statistik" (2014, 2015).

303 Figure 2 shows the annual quantities of microplastic emissions from sewage sludge and compost ($QMP_{f,t}$) for the period 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. This leveling off results from the decreasing quantities of sewage sludge applied to agricultural soils (Fig 2) combined with the increasing concentration of microplastics in sludge (Fig Annexe-1). The higher concentration of microplastics in sewage sludge leads to annual emissions of these pollutants three to five times higher for sewage sludge than for compost. Thus, the fact that the emission factor of sewage sludge ($EF_{sludge,2016} = 0.6\%$) is higher than the emission factor of compost ($EF_{compost,2016} = 0.04\%$) compensates largely for the lesser amount of sewage sludge applied to land compared to compost. Indeed, the simulated results of microplastic quantities and the subsequent results depend strongly on the assumptions of the microplastic concentration in sludge and compost. We selected the high concentrations provided by the literature by following the worst-case assumption, which could result in an overestimation of the results.

317 Figure 2 presents the accumulated quantities of microplastics emitted from sewage sludge and compost in agricultural soils ($QMPS_{f,t}$) over the period 1983 to 2016. The more significant increase in sewage sludge microplastics results from the assumption of the exponential increase in microplastic concentration from synthetic fiber production (see Appendix A-1.0). For the year 2016, the total quantity of microplastic originating from both sewage sludge and compost was estimated at 3,084 t, with 2,452 t originating from sewage sludge and 632 t from compost. For the period 1983 to 2016, total emitted microplastics amounted to 58,997 t, with 48,733 t originating from sewage sludge and 10,264 t from compost. Emissions are approximately five times higher for sludge than for compost.

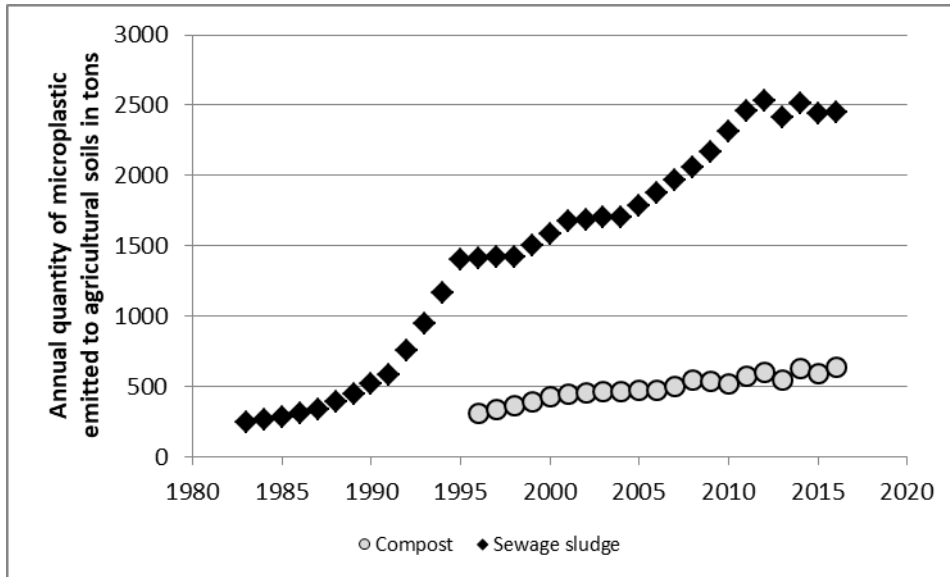


Figure 2. Quantities of microplastic emitted annually from sewage sludge and compost into agricultural soils in Germany. Source: Own computations based on: UBA (2020): Bioabfälle, BMEL (2019), Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 "Statistik" (2014, 2015).

326 3.2 Concentration of microplastic and utilized agricultural area polluted with 327 microplastics

328 We simulate two worst-case scenarios to estimate the concentration of microplastic in agri-
329 cultural soils and the utilized agricultural area (UAA) with potentially polluted soils. One
330 simulates the highest concentration and the other simulates the largest extent of potentially
331 polluted area. We simulate both worst-case scenarios for the emission of microplastic by
332 sewage sludge and by compost with each of three different fertilization intensities.

333 Concerning the highest concentration worst-case scenario, we assume that the fields received
334 sludge or compost in each year of the simulation periods. Thus, microplastic emitted from
335 sludge could have accumulated in these fields between 1983 and 2016 and from compost
336 between 1990 and 2016. The area with the highest concentration is limited to the fertilized
337 area of the first year. Only this area could have received microplastic from organic fertilizers
338 every year.

339 To determine the largest polluted UAA worst-case scenario, we use the year with the highest
340 quantity of sludge and compost applied to the land. The quantity determines the area, which
341 received, at least in one year, microplastic from the organic fertilizer. The year 1995 is estab-
342 lished with the largest quantity of sludge and 2016 for compost. Figure 3 plots the simulated
343 microplastic concentration in soils and the polluted UAA.

344 We simulate an accumulation of microplastic at 40 mg/kg (Point A) for the fields receiving
345 an annual application of sludge (for 33 years, between 1983 and 2016), with the highest ferti-
346 lization intensity. We expect to find this high concentration on a potentially polluted area of
347 1.3% UAA (i.e., 0.22 million ha). For compost we compute a concentration of approximately
348 30 mg/kg on 0.5% UAA (i.e., 0.08 million ha) (Point D).

349 Points I and L represent the maximal polluted UAA with any microplastic present after at
350 least one application of sludge or compost between 1983 and 2016 at the lowest simulated
351 fertilization intensity. These fields add up to 19% of UAA (3.17 M ha) for sludge and 3% of
352 UAA (0.5 M ha), for compost, with correspondingly marginal microplastic concentrations.

353 The aggregated UAA with highest concentration from sludge or compost does not exceed 2%
 354 UAA (~ 1.8% UAA = 1.3% UAA + 0.5% UAA). The maximum UAA with some
 355 microplastic pollution resulting from at least one application of sludge or compost, does not
 356 exceed in total about 20% of UAA (~22% UAA = 19% UAA + 3% UAA).

357 In situ the concentration of microplastic in agricultural soils can be expected to be much low-
 358 er than simulated in the worst-case scenarios, because the yearly application of sludge or
 359 compost might not have been carried out in practice. The enrichment by organic matter might
 360 be reached at a certain point and does not require further fertilization with sludge or compost.

361 The scenarios assuming medium and low fertilization intensity result in lower concentration
 362 than for the scenario of high fertilization intensity. The concentrations are Sludge 16 and
 363 7 mg/kg (Point B and C) and Compost 20 and 10 mg/kg (Points E and F). The total potential-
 364 ly polluted area adds up to about 10% of UAA (= 1.61 M ha) (Points H+K) for medium ferti-
 365 lization intensity 22% of UAA (= 3.56 M ha) (Points I+L) for low fertilization intensity.

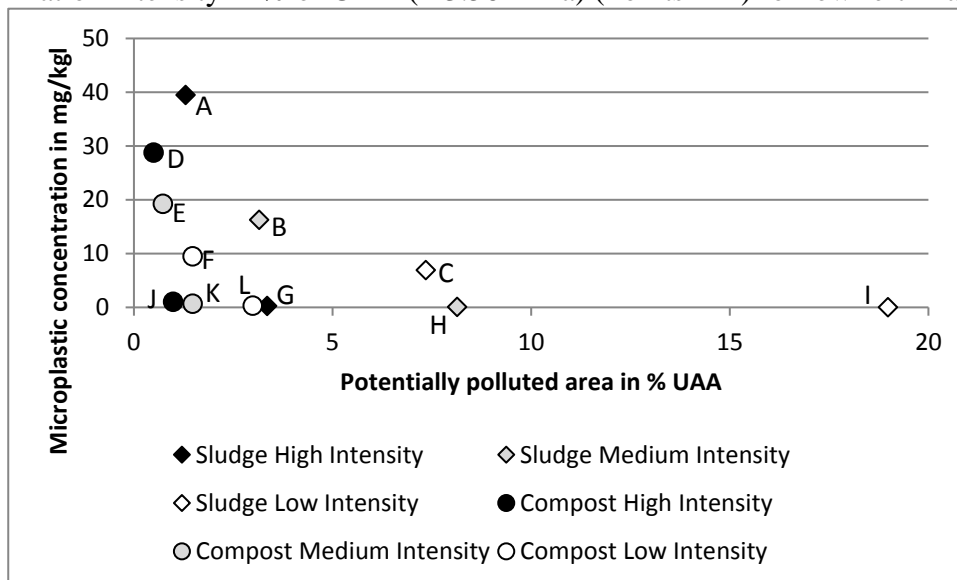


Figure 3. Microplastic concentrations in agricultural soils and extent of polluted area in the simulated scenarios of high, medium and low fertilization intensity for the year 2016.

Notes: 1 % of UAA = 0.167 M ha. Scenario assumptions: annual application rates in the: (i) high fertilization intensity scenario: 1.6 t/ha for sludge and 10 t/ha for compost, (ii) medium fertilization intensity scenario: 0.6 t/ha for sludge and 6.7 t/ha for compost. (iii) low fertilization intensity scenario: 0.3 t/ha for sludge and 3.3 t/ha for compost. Application duration: sludge 1980 to 2016, for compost from 1990 to 2016. Soil density: 1.2 g/cm³. Ploughing horizon: 0.3 m.

366 The simulations provide benchmark values of concentration and potentially polluted UAA for
 367 the whole of Germany. However, at the regional scale the concentrations and the UAA can
 368 vary. Figures 4a to 4d present the potentially polluted UAA at regional county level in the
 369 reference year 2016 for low fertility intensity (Fig a and d) and high fertility intensity (Fig b
 370 and c). The snap-shot for the year 2016 illustrates significant regional heterogeneity of the
 371 potentially polluted UAA.

372 In the high fertilization scenario with sludge, the potentially polluted soils reach 1 to 4 % of
 373 utilized agricultural area (UAA) in the north-western half of Germany, where farmers have
 374 traditionally been applying more sludge as fertilizer than in the southern regions (Aqua Con-
 375 sult Baltic 2015). In the southern regions, the regional governments recommend not applying

376 sludge as organic fertilizer (StaLa-BW 2021, UM-BW 2021, LfU 2020). Thus, in Baden-
 377 Württemberg (South-East) the agricultural disposal of sludge as fertilizer has been nearly
 378 completely abandoned and disposal has switched to thermal recycling and to export of sludge
 379 (StaLA-BW, 2021).

380 In urban regions the polluted area is higher because of high supply of sludge from many in-
 381 habitants. The low transportation value of sewage sludge limits the transportation distance
 382 from waste water treatment plants to the sites of application. Consequently, the application of
 383 sewage sludge as a fertilizer is higher in regions close to bigger cities, such as Hamburg,
 384 Hannover, and in the north of the urban cluster the Ruhr Area, (Dortmund, see Figures 4a and
 385 b). The regional distribution of area polluted by compost follows the similar pattern, with the
 386 difference that compost is used as fertilizer. Polluted areas of 4 to 6 % of UAA can be found
 387 also around Frankfurt, Stuttgart and Munich (see, Figures 4c and d).

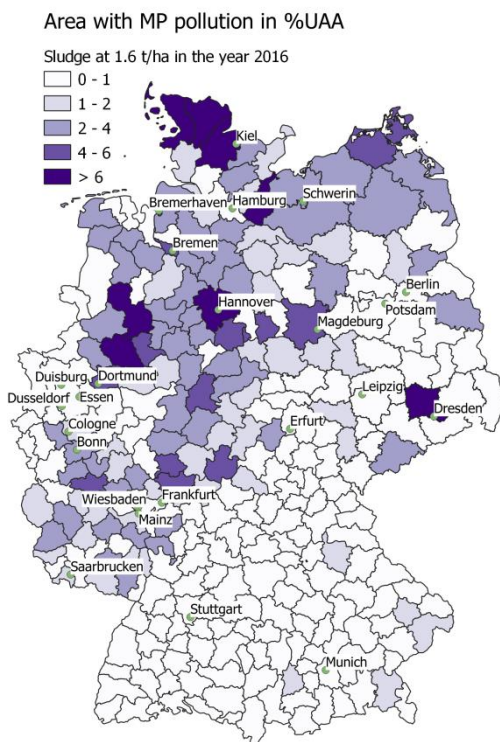


Fig 4a. Area potentially polluted by microplastic from sludge in share of UAA under fertilization intensity of 1.6 t/ha

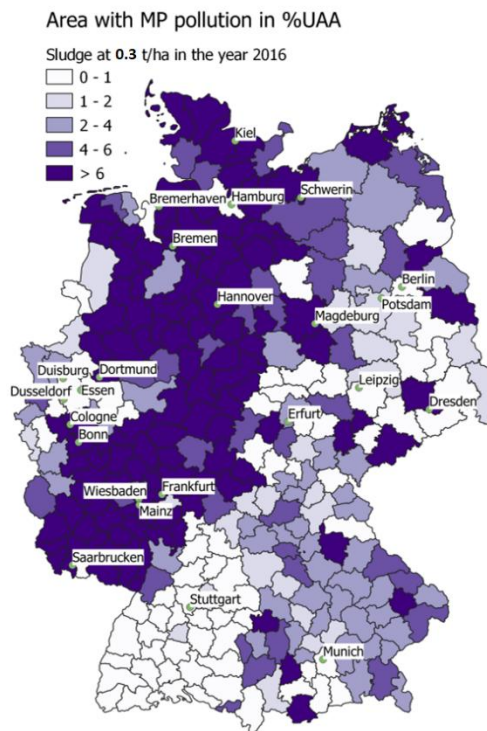


Fig 4b. Area potentially polluted by microplastic from sludge in share of UAA under fertilization intensity of 0.3 t/ha

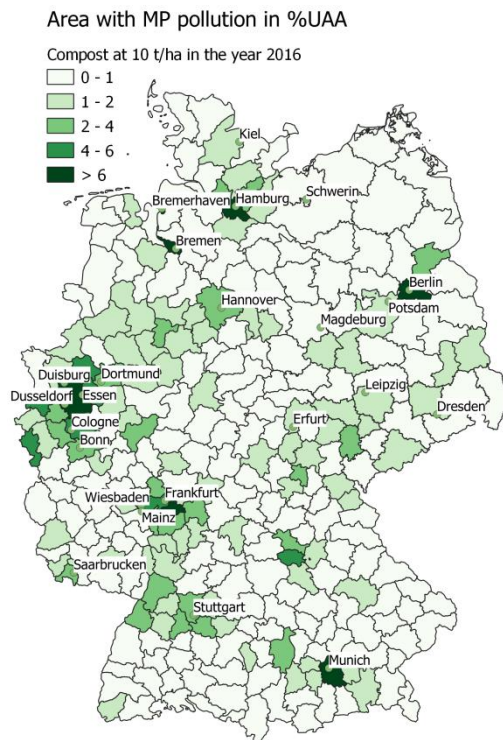


Fig 4c. Area potentially polluted by microplastic from compost in share of UAA under fertilization intensity of 10 t/ha

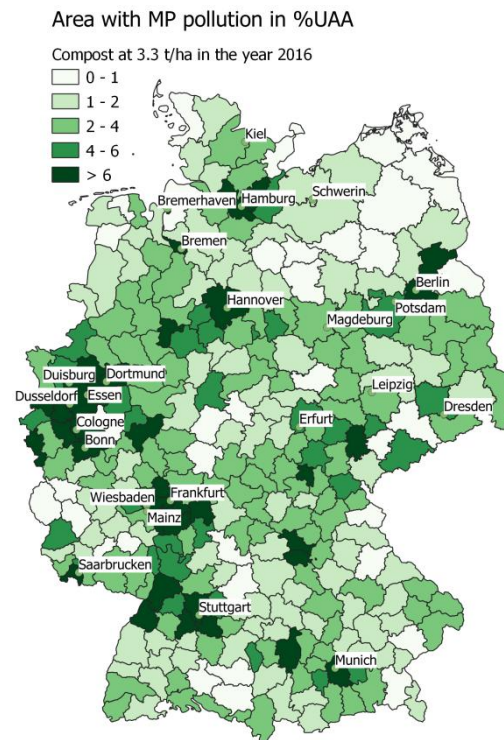


Fig 4d. Area potentially polluted by microplastic from compost in share of UAA under fertilization intensity of 3.3 t/ha

388 The regional analysis suggests that the regions around big cities are a hot-spot where many
 389 sites with potentially polluted soils can be expected. These regions may require particular
 390 focus for environmental assessment. Furthermore, these regions could also be of interest for
 391 in situ analysis of microplastic in soils on suitable sample fields.

392 3.3 Evaluating abatement measures

393 The simulated model results indicate that the microplastic concentration and the polluted area
 394 can regionally be relatively high. Abatement measures may be required, depending on how
 395 future research quantifies the thresholds of damage, the thresholds of concentration or the
 396 thresholds of area. The definition might not only be based on negative impacts of
 397 microplastic in the terrestrial environment. Such thresholds can also consider potentially neg-
 398 ative impacts caused by the emissions of microplastics from soils (e.g., transport into aquatic
 399 systems by soil erosion).

400 3.3.1 Scenarios of abatement measures

401 To analyze the ways to reduce microplastic emissions from sewage sludge and compost, we
 402 simulate abatement measures for sludge and compost according to environmental policy prin-
 403 ciples. Filter systems for washing machines, and detection systems for bio-waste collection
 404 represent measures in accordance with the “reduction at the source” principle. Thermal recy-
 405 cling would rather represent an “end-of-the pipe” treatment.

406 Furthermore, filter and detection systems for households and industry follow the “polluter-
 407 pays-principle”, whereas thermal recycling (end-of-the-pipe solution) might create the costs
 408 for farmers by halting the application of sludge and compost as fertilizer. We compute two
 409 indicators for the reference year 2016 assessing relative cost-efficiency and effectiveness of
 410 the simulated measures: the marginal abatement costs and the abatement effect. We compare

411 the results of the scenarios with a reference, without any measure to avoid the microplastic
 412 emissions. To evaluate the effectiveness of the measures in the long term, we also simulate
 413 the evolution of microplastics in soils up to the year 2060.

414 **Scenario: No-Measure**

415 We assume that the land-based disposal of sludge and compost as organic fertilizer continues
 416 without any abatement measure, without any extra-costs and without reduction of
 417 microplastic emissions. For the sludge we assume that the content of microplastic remains at
 418 the level defined for the reference year 2016 and for the long-term simulation, we assume an
 419 annual increase in its use as observed as average for the last five years from 2015 to 2020.
 420 For sludge disposal in Germany, the scenario "No-Measure" is not realistic, because in Ger-
 421 many the sludge from bigger waste water treatment plants will be mandatorily thermally
 422 recycled. Thus, this scenario is counter-factual serving as comparison.

423 For compost the scenario "No-Measure" represents the current situation in reality. Although
 424 there are defined thresholds for the maximum content of non-organic items in compost (i.e.,
 425 at 1%, Kehres 2019), there is currently no specific measure to reduce the content of
 426 microplastic emissions to agricultural soils significantly below this threshold. For the long-
 427 term simulation, we assume that infrastructure for biowaste collection will improve and allow
 428 for the collection of additional biowaste, which was not collected from all households in
 429 2016. Thus, up to the year 2060 we assume an annual increase of 1%, which increases the
 430 quantity of collected bio-waste by about 50% compared to the 2016 value. This value corre-
 431 sponds to the estimate of the hidden potential of biowaste by Herrmann et al. (2017:7). We
 432 assume that the microplastic content in compost remains stable over this time.

433 **Scenario: Thermal recycling of sludge and bio-waste (end-of-the-pipe)**

434 For sludge in Germany this scenario is close to the reality. After 2030 most of the sludge will
 435 be thermally recycled from waste water treatment plants with population equivalents greater
 436 than 50,000. Waste water treatment plants treating smaller volumes can continue with
 437 landbased disposal (Rokosch 2019). We simplify the scenario assumption so that the sludge
 438 from the smaller waste water treatment plants is also thermally recycled.

439 For compost, we assume that the fraction of biowaste originating from households and indus-
 440 try is thermally recycled, as we assume that most of microplastics enter the compost from
 441 these sources. We assume that bio-waste from landscaping (e.g., cuttings), continues to be
 442 recycled as compost and disposed on the land.

443 Thermal recycling results in a reduction of microplastic emission by 100% for both sludge
 444 and compost. We assume that microplastic accumulates in the soil and does not migrate or
 445 decompose, thus in the long-run, the projected soil concentration remains in 2060 at the level
 446 of 2016.

447 To estimate the abatement costs, we consider (i) technical costs for the thermal recycling pro-
 448 cess, (ii) cost for the loss of nutrients which are not available for agricultural production and
 449 (iii) cost of CO₂ emissions.

450 We assume the technical cost for thermal recycling for sludge as the additional costs com-
 451 pared to the land-based recycling as being higher than for compost. The energy demand for
 452 incinerating sludge is higher than for bio-waste. We do not consider the costs for building the
 453 thermal recycling plants. Considering these fixed costs will increase the cost of thermal recy-
 454 cling.

455 To derive the costs for the lost nutrients, we assume that farmers replace the lost nutrients
 456 with mineral fertilizers and straw for substituting the organic matter. To derive the cost of

457 CO₂ emissions, we assume that during thermal recycling the carbon in the organic matter is
 458 burned completely to CO₂. This CO₂ is released to the atmosphere as greenhouse gas, where
 459 it contributes to global warming. We simplify our assumption and consider only the emis-
 460 sions resulting from burning carbon. We also exclude the emission of other greenhouse gases,
 461 which might be emitted during incineration (nitrogen oxides, etc). We assume that in land-use
 462 based recycling, the carbon from the organic matter in sludge and compost will be fixed in
 463 the soils for longer durations. Thus, we simulate carbon price to quantify the cost of these
 464 emissions and vary them from 50 to 200 EUR/t CO₂eq.

465 **Scenario: Filter systems in washing machines**

466 We assume that 75% of microplastic in wastewater and sewage sludge is released from the
 467 textile fibers during the washing of clothes in private households and industry. Filters applied
 468 to the washing machines in households can reduce the emission of textile fibers by up to
 469 80%. In this scenario we assume that each washing machine in Germany is equipped by a
 470 filter for textile fibers.

471 This scenario is oriented from the abatement measure foreseen in France. As the leading Eu-
 472 ropean country, France intends to make it compulsory for washing machine manufacturers to
 473 equip new machines with filters starting in January 2025 (Ministère de la Transition
 474 écologique et solidaire 2020). This measure would be in line with the European plastic strate-
 475 gy (European Union 2012) and would help reduce the emissions of microplastic from house-
 476 holds. To estimate the costs for the filter systems, we derive the costs for the technical
 477 equipment of washing machine with filters and for replacing the filter membranes. We com-
 478 pute annual costs, based on the 10-year lifespan of a washing machine. As the abatement
 479 measure reduces only microplastic emission from textile fibers (i.e., 75% of the total
 480 microplastic in sludge), the total concentration of microplastic content in sludge is reduced by
 481 totally 45%. We assume that microplastic emissions to wastewater and sludge from other
 482 sources stay unchanged, although for some sources a reduction can also be expected. In some
 483 EU countries some producers have already banned the use of plastic microbeads in personal
 484 care products and detergents (e.g., in the Netherlands, France, Ireland, Sweden, UK and Ita-
 485 ly).

486 **Scenario: Detection system for bio-waste collection**

487 The microplastic content in compost results mainly from packaging material. Detection sys-
 488 tems in garbage trucks, which collect the biowaste from households and industry, allow for
 489 the quantification of the non-organic material in the biowaste. Thus, excessively high levels
 490 of plastic during the collection process can be detected in the bio-waste. Plastic contaminated
 491 bio-waste is not collected and households are informed that their biowaste does not reach the
 492 required quality standard. The households have to pay extra fees for its disposal. We assume
 493 that quality control combined with a monetary penalty will improve the quality of the
 494 biowaste and reduce the plastic content by 90%. We assume that the same system and policy
 495 can be applied for the collection of industrial biowaste. This scenario is based on a detection
 496 system and policy measures tested in some German communities (see Appendix A-3.5.1). To
 497 derive the costs, we apply the annual cost for the detection system to the total number of gar-
 498 bage trucks collecting biowaste in Germany. Since, statistical data on the total number of
 499 garbage trucks could not be retrieved, we estimated the number of German garbage truck for
 500 biowaste and varied the number in a sensitivity analysis (see Appendix A-3.5.1).

501 Table 2 summarizes the assumption of the scenarios for analysing the abatement measures.
 502 Appendix A-3.5 presents the assumption and the computations and source in more detail.
 503 Indeed, the data and the results can only provide a rough estimation because the assumptions

504 for the simulated systems are based on pioneering techniques. Thus, the interpretation of the
 505 results is limited to ranges and should not be considered as exact figures as marginal abate-
 506 ment costs are used as indicators for ordinal comparison rather than for the interpretation of
 507 absolute costs. Furthermore, the results require future updating and revision because future
 508 technological progress might change the assumptions for costs, prices and effectiveness.

509 **Table 2: Overview on reduction rate and costs.**

	Sludge		Compost/Bio-Wast	
	Thermal recy- cling	Filter System	Thermal recy- cling	Detection System
Abatement Reduction rate	100%	45%	100%	80%
Costs				
Cost of tech- nique	2.5 EUR/(t dry matter)additional cost compared to landbased appli- cation	35 EUR per filter and washing mash- ing, 0.8 EUR per filter mem- brane	0.90 EUR/(t dry matter), additional cost compared to landbased appli- cation	3965 EUR per garbage truck for biowaste collection per year
Cost of Nutri- ent Losses	144 EUR/t		55 EUR/t	
Cost of CO2 emissions	varied for from 0 to 200 EUR/t CO ₂ eq		varied for from 0 to 200 EUR/t CO ₂ eq	
Projection to 2060				
Quantity of sludge and compost ap- plied to soils	Reduced to zero tons in 2021	annual applica- tion of sludge until 2060 based on the average appli- cation from 2015 to 2019	Increase of col- lected biowaste from households by 0.5% annually until 2060	

510 Notes: Filter systems reduce fibers from textile washing by 80%, which accounts for 45% of the total microplastic load in waste-water.
 511 Detection systems reduce the quantity of non-organic waste disposed in the bio-waste collection bin by 80%.

512 3.3.2 Cost-efficiency and effectiveness

513 Table 3 presents the marginal abatement cost and the abatement effect for the simulated
 514 abatement measures. For sludge, the marginal abatement costs are significantly higher for the
 515 filter system than for thermal recycling, even under extremely high assumptions for the car-
 516 bon prices at 200 EUR/t CO₂eq. The filter system abates with 1,000 t less than the half of the
 517 abatement reached by thermal recycling scenario with 2500 t. Reducing more microplastics
 518 would require additional measures (e.g., technical standards) to abate emissions from the
 519 cleaning of containers (17% of the total load), cosmetics and personal care products (14%)
 520 and cleaning products (3%).

521 Removing microplastics as an ingredient has already been considered by some producers of
 522 personal care and cleaning products who can retain market shares by “greening” their prod-
 523 ucts. Since microplastics are publicly discussed as pollutants, consumers favor products with-
 524 out microplastics. In some products, microplastics can be replaced by more environmentally
 525 friendly particles to achieve the abrasive or covering effects (e.g., natural crystals: salt, sand).

526 However, removing the microplastic, which cannot be abated by the filter system even at zero
 527 cost, would reduce the marginal abatement cost to only 120 EUR/kg. The costs for the filter
 528 system is still higher than the abatement cost computed for the thermal recycling at carbon
 529 prices at less than 200 EUR/t CO₂eq (Table 2).

530 The limited abatement effect of the filter system (i.e., reduction by 45%) and the high costs
 531 make the filter system less cost-efficient and less effective than thermal recycling. Thermal
 532 recycling of sludge has other advantages not considered here. Thermal recycling allows for
 533 recycling of phosphorous, which can reenter the nutrient cycle as a mineral fertilizer. Addi-
 534 tionally, thermal recycling avoids the release of pollutants other than microplastic into the
 535 soil and aquatic systems (e.g., antibiotics, heavy metals and pathogens).

536 Thus, the results confirm the planned thermal recycling of sludge from bigger waste water
 537 treatment plants as a cost-efficient and effective measure. However, washing machine filter
 538 systems could still be considered as an abatement measure for households connected to waste
 539 water treatment plants with population equivalents lower than 50,000, which will be still al-
 540 lowed to dispose of their sludge by land (Rokosch 2019). The regional application of filter
 541 systems would allow for an effective reduction of microplastic emission into agricultural
 542 soils. As less cost-efficient than thermal recycling, however, the filter system would allow the
 543 disposal of sludge according to the objectives of the European Circular Economy Strategy
 544 and in line with soil and environmental protection (European Union 2020b).

545 **Table 3: Average MP abatement costs and abatement effect of the simulated abatement**
 546 **measures**

Abatement costs		Sludge	Bio-waste used for compost		
			Number of garbage trucks used for biowaste collection		
Assumptions of fitted number of garbage trucks			1,400	2,500	3,000
Filter system for washing machines	[Eur/kg]	264	NA	NA	NA
Detection system for biowaste collection	[Eur/kg]	NA	9	16	19
Thermal recycling of sludge or biowaste, carbon price = 200EUR/t CO ₂ eq	[Eur/kg]	110	262	262	262
Thermal recycling, carbon price = 100EUR/t CO ₂ eq	[Eur/kg]	85	164	164	164
Thermal recycling, carbon price = 50EUR/t CO ₂ eq	[Eur/kg]	73	115	115	115
Thermal recycling, no carbon price	[Eur/kg]	61	66	66	66
Abatement effect					
Filter system for washing machines	[tons]	1112	NA	NA	NA
Detection system for biowaste collection	[tons]	NA	612	612	612
Thermal recycling, carbon price = 200EUR/t CO ₂ eq	[tons]	2450	680	680	680

547 For bio-waste, the marginal abatement cost for the garbage truck detection system is cheaper
 548 than the thermal recycling, even at zero cost emission costs (66 EUR/kg) and even with the
 549 high assumption of fitting out 3,000 garbage trucks at 19 EUR/kg. The marginal abatements
 550 costs from losses of nutrients are relatively high for compost (see Appendix A-3.0). Thus, the
 551 abatement of emission at the source of pollution appears to be more cost-efficient than the
 552 end-of-pipe solution. Fitting out more than 10,000 garbage trucks would let the abatement
 553 costs be higher than the cost for the filter system. However, a number of 10,000 garbage
 554 trucks for the bio-waste collection seems to be an extremely high given that the number of

555 garbage trucks (for biowaste and other waste) in Germany is estimated to be 12,000 (VAK
 556 2021). In terms of effectiveness, the reduction of microplastics by 612 tons using the detec-
 557 tion system is comparable to the reduction by thermal recycling with a 680-ton reduction.

558 3.3.3 Effectiveness in the long-run

559 To analyse the effectiveness of the abatement measure over time, we simulate a period from
 560 2016 to 2060. Indeed, the simulation period of more than 40 years appears to be quite long,
 561 and many changes can occur during this time in terms of environmental policies and techno-
 562 logical progress (e.g., development of completely biodegradable (bio) plastics or of textiles
 563 with reduced fiber emissions). Thus, the *ceteris paribus* assumption for the simulation period
 564 is important to consider.

565 Figure 5 displays the evolution of the concentration over time under the worst-case assump-
 566 tion of the highest fertilization intensity, resulting in the highest future pollution pressure.
 567 This means, strong *ceteris paribus* conditions over the long term. In the No-Measure scenar-
 568 io, the concentration of microplastic from sludge will reach about 50 mg/kg in 2020 and
 569 140 mg/kg in 2050; with filter systems applied in 2021, the concentration reaches 100 mg/kg
 570 in 2050. With thermal recycling the concentration remains below 60 mg/kg in 2060. For
 571 compost without changes, the concentration will reach about 30 mg/kg in 2020 and 65 mg/kg
 572 in 2050. With simulating the start of using detection systems or thermal recycling in 2021, the
 573 concentration increases at a low rate and remains until 2060 at less than 40 mg/kg. The simu-
 574 lation of the microplastic concentration in the soil over the long term illustrates that the detec-
 575 tion system effectively reduces the emissions of microplastic from compost into agricultural
 576 soils.

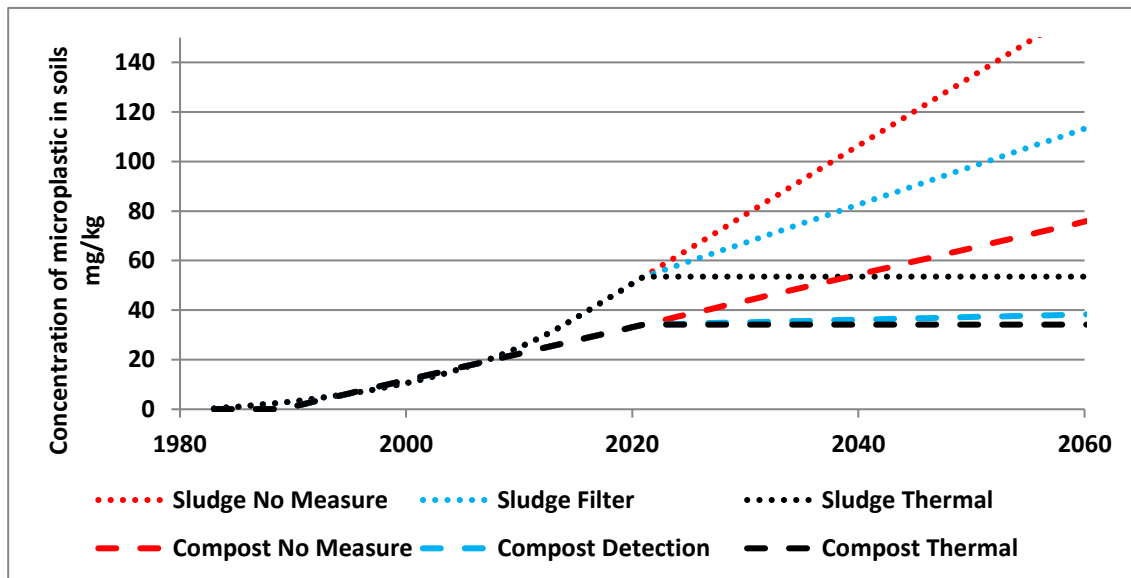


Fig 5: Effectiveness of simulated abatement measures in the long run

Note: in the scenarios “Compost Thermal” and “Compost Detection” and we refer to the thermal recycling of bio-waste and the detection system applied to the collection of bio-waste.

577 4 Conclusions

578 The new environmental problem of microplastic pollution represents a new challenge for
 579 policy makers to follow the principles of precaution and prevention under respecting scien-
 580 tific evidence and appropriateness. Scientific evidence is required for the evaluation of the
 581 microplastic pollution, which considers all economic agents and stakeholders along the pollu-
 582 tion chain (e.g. society and farmers) (Henseler et al. 2020). Wholistic evaluation approaches
 583 and interdisciplinary research is required to understand the complex of microplastic pollution,

584 as it is required for many problems in environmental economics (Melgar-Melgar and 2020,
585 Hagens 2020).

586 The normatively simulated results allow the conclusion that the current microplastic concen-
587 tration from sludge or compost (2020) should not exceed concentrations between 40 and
588 50 mg/kg, which is computed under the worst-case assumption. The potentially polluted area
589 with such a high concentration should not exceed the relatively small agriculturally used area
590 of 2%. Area polluted with some microplastic from at least one application should not exceed
591 22% (i.e., around 20%) of utilized agricultural area, which is a considerable area, however,
592 which also includes fields where sludge or compost have been applied only one time and
593 where the concentration of microplastic is expected to be marginal. The computed values for
594 concentration and area can flow into the discussion between researchers and policy makers as
595 scientific data required for policy design. The regional analysis shows that in regions close to
596 bigger cities, more polluted UAA should be expected where regional assessments and
597 measures could be required.

598 Applying detection systems for the collection of biowaste appears to be a cost-efficient and
599 effective abatement measure to avoid microplastic emissions from compost, and it the strate-
600 gy of a circular economy to be followed (European Union 2020b). For sludge, the thermal
601 recycling appears to be more cost-efficient and effective than equipping washing machines
602 with filters. However, for regions where land-based disposal of sludge will continue, filters
603 systems could be an option to reduce soil pollution. The simulated results also can provide a
604 starting point for information on the cost and benefit of mitigation measures.

605 The results presented in this study are based on simulations with a normative model. The as-
606 sumptions of the model, the scenarios and the results, need to be revised and up-dated accord-
607 ing to the relatively fast developing research field “microplastics”. However, the presented
608 model-based values can contribute as scientific data on soil pollution as required by the Eu-
609 ropean legislation to discuss, design and evaluate environmental policies. Preventing soil pol-
610 lution has gained recent relevance within the European Green Deal (European Union 2019)
611 directly addressed by the European “New Soil Strategy” (European Union 2021) and by the
612 “Action Plan towards a Zero Pollution Ambition for Air, Water and Soil” (European Union
613 2020a). As findings for the study region Germany, the result can also be applied for the dis-
614 cussion on countries with comparable of usage of sludge and compost in agriculture.

615 The application of normative models can be a complementary approach to methods used by
616 analytical science. An interdisciplinary and iterative research approach between modelling
617 and analytical science can be a fruitful way to close the knowledge gaps on microplastics.
618 Model simulations can help estimate concentrations, assess polluted areas and to identify sites
619 interesting for in-situ. The evidence from analytical science is required to calibrate and vali-
620 date the simulation models. Normative simulation models can be developed complementarily
621 to analytical science methods and be prepared to support policy decision-making on a still
622 unknown, but already ubiquitous pollutant: microplastics in agricultural soils.

623 **5 Literature**

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942

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

945

946

Appendix

947

948 **Appendix A-1.0: Assumptions for the evolution of microplastic content in sewage sludge**

949 Textile fibers are the largest source of microplastics in sewage sludge with a share of 57%.

950 Textile fibers are released into wastewater during the laundering processes in private house-

951 holds and industry (Zambrano et al. 2019, Carney Almroth et al. 2017, Cesa et al. 2017, De

952 Falco et al. 2017, Hernandez et al. 2017, Napper and Thompson 2016, Pirc et al. 2016). We

953 consider polyester fibers to be representative of all present textile fibers (e.g., polyester, ny-

954 lon, acrylic). We assume that the global production of polyester fibers determines the use and

955 subsequent laundering of textiles containing synthetic polymer fibers. Thus, we assume that

956 the increase in the production of fibers is indicative of the evolution of these emissions to

957 waste-water.

958 Polyester production increases exponentially from 3.4 million tons in 1975 up to

959 53 million tons in 2016 (Fig.1). We fit an exponential model to describe the evolution of the

960 production of polyester fibre production and we define the level of the reference year 2016 to

961 represent 100% of microplastic concentration in sewage sludge. Based on this model, we de-

962 rive that in the years before 1990, the microplastic concentration accounted for less than 15%

963 of the microplastic concentration in sewage sludge found in 2016.

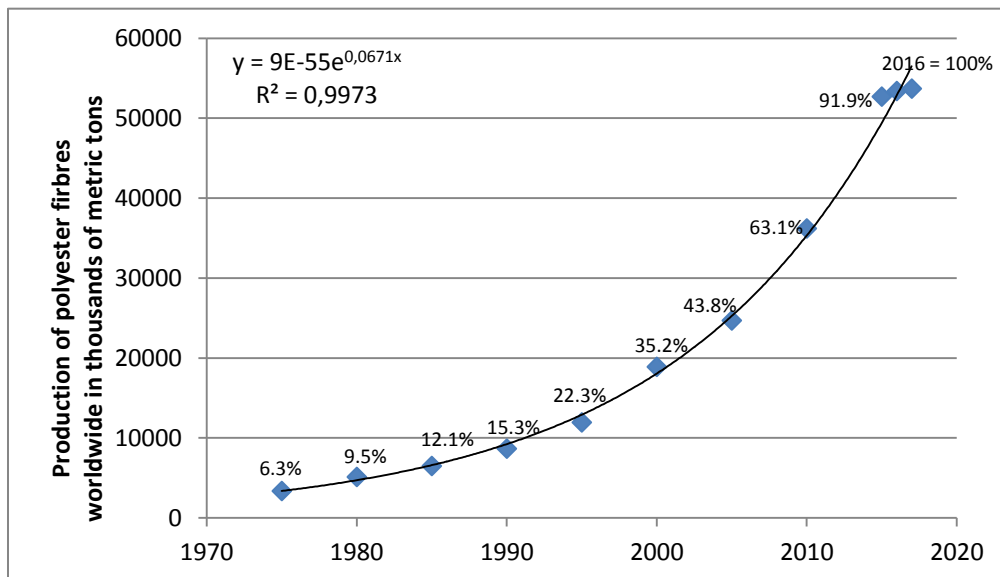


Figure 1. Production of polyester fibers worldwide from 1975 to 2017. The missing data is approximated using a linear interpolation. Source: Own computation based on Statista (2019)

964

965 **Appendix A-2.0: Additional information on soil protection and fertilizer regulation**

966 Regulations on the disposal of bio-waste protecting the soils from contamination by pollu-
967 tants in bio-solids (i.e., Bundes-Bodenschutzgesetz – BBodSchG, BBodSchG 2017); Bundes-
968 Bodenschutz- und Altlastenverordnung –BbodSchV, BBodSchV 2017). Regulations on the
969 disposal and recycling of sewage sludge and compost regulate the disposal practices of sew-
970 age sludge and compost on agricultural land and define pollutant thresholds (i.e.,
971 Klärschlammverordnung – AbfKlärV, Bioabfallverordnung – BioAbfV, BioAbfV 2017).
972 Regulations on *fertilizer* **and** product certificates define the thresholds for pollutants in ferti-
973 lizer (Düngemittelverordnung – DüMV, DüMV 2019) and quality certificates for compost).
974 Regulations on fertilization specify the good agricultural practice for the application of organ-
975 ic fertilizers (Düngeverordnung – DüV, DüV 2017).
976

977 **Appendix A-3: Computation of abatement costs and effects**

978 **Appendix A-3.0: Overview on the marginal abatement costs**

979 We derive the marginal abatement costs for the different abatement measures based on in-
 980 formation researched from different sources. Partially the sources are information on the
 981 products provided by the producers (i.e., the filter system for washing machines and the de-
 982 tection system collecting biowaste). Thus, this information might require updates in further
 983 research work according to future scientific reviews and technological progress. Table A-3.0
 984 provides an overview on the abatement costs for different cost (e.g., incineration, nutrients)
 985 and scenarios assumptions (e.g., CO₂ price). Appendix A-3.1- to A-3.5 present the computa-
 986 tions in more detail.

987 **Table A-3.0: Overview on the marginal abatement costs**

	Scenarios	Sludge	Compost ^{a)}
Thermal recycling			
Costs for incineration [EUR/kg]		0.44	1.07
Losses of nutrients [EUR/kg]		24	65
Costs for CO ₂ emissions [EUR/kg]	High price	49	195
	Medium price	24	98
	Low price	12	49
Marginal abatement costs [EUR/kg]	High price	73	262
	Medium price	49	164
	Low price	37	115
	Zero price	24	65
Filter System			
Cost for filter system and replacement [EUR/kg]		264	
Detection system			
Assumption of number of garbage trucks [EUR/kg]	High number		19
	Medium number		16
	Low number		9

a) Note that the measures here refer to compost as the organic fertilizer, however, the processors of thermal recycling and the application of a detection system apply to bio-waste

988 **Appendix A-3.1: Abatement costs – thermal recycling: incineration**

989 One component of the costs for thermal recycling is additional costs for incineration com-
 990 pared to the land-based disposal. This value is based on data provided for the different ways
 991 of disposal for sludge. We assume these costs for sludge to be the option with the highest
 992 costs (i.e., mono incineration). For compost we derive a lower value by assuming that com-
 993 post is first dried and then incinerated. The costs for compost might be overestimated. How-
 994 ever, given the relatively small share of the total costs (see Table A-3.0), we expect that this
 995 overestimation does not significantly change the magnitude of the computed marginal abate-
 996 ment costs. We do not consider the costs for the infrastructure or the transport for incinera-
 997 tion.

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1001

1002 **Table A-3.1.1: Computation of abatement costs for thermal recycling – incineration of**
 1003 **sludge**

	Value	Source
Abatement costs		
Thermal recycling of sludge [Eur/t]	6.84	Rokosch (2018:64)
Land-based disposal [Eur/t]	4.32	Rokosch (2018:64)
Additional costs for thermal recycling [Eur/t]	2.52	Own Computation
Sludge applied as fertilizer [M t]	0.42	Own Computation
Additional costs for thermal recycling [M EUR]	1.07	Own Computation
Abatement		
Sludge applied as fertilizer [M t]	0.42	Own Computation
Microplastic content [% dry matter]	0,6%	Own Computation
Microplastic abated from sludge [tons]	2,500	Own Computation
Marginal abatement costs		
Marginal abatement costs [EUR/t]	435.54	Own Computation
Marginal abatement costs [EUR/kg]	0.435	Own Computation

1004 **Table A-3.1.2: Computation of abatement costs for thermal recycling – incineration of**
 1005 **biowaste**

	Value	Source
Abatement costs		
Thermal recycling of bio-waste [Eur/t]	5.22	Rokosch (2018:64)
Land-based disposal [Eur/t]	4.32	Rokosch (2018:64)
Additional costs for thermal recycling [Eur/t]	0.90	Own Computation
Bio-Waste from industry and households in compost [M t]	0.80	Own Computation
Additional costs for thermal recycling [M EUR]	0.73	Own Computation
Abatement		
Compost applied in agriculture [M t]	1.7	Own Computation
Microplastic content [% dry matter]	0.04%	Own Computation
Microplastic abated compost [tons]	680	Own Computation
Marginal abatement costs		
Marginal abatement costs [EUR/t]	1,070	Own Computation
Marginal abatement costs [EUR/kg]	1.07	Own Computation

1006 **Appendix A-3.2: Abatement costs – thermal recycling: Nutrients**

1007 To derive the monetary losses caused by the losses of nutrients, which are in case of thermal
 1008 recycling no longer available for the agricultural sector, we assume that all nutrients are not
 1009 available and need to be substituted by mineral fertilizer and by straw (for the organic mat-
 1010 ter). We do not consider that phosphorus can enter the nutrition cycle again after the incinera-
 1011 tion of sludge.

1012

1013 **Table A-3.2.1: Computation of abatement costs for thermal recycling – costs from losses**
 1014 **of nutrients from sludge and bio-waste**

	Bio-waste (households and industry)	Bio-Waste (landscaping)	Sludge	Computations based on source
Nutrient quantity				
Dry matter [M kg]	495.9	522.9	14.7	WBD (2008), Kehres and Reinhold (2008)
N-content [M kg]	1.80	1.55	6.72	WBD (2008), Kehres and Reinhold (2008)
NH4-N content [M kg]	0.11	0.01	1.85	WBD (2008), Kehres and Reinhold (2008)
P2O5 content [M kg]	12.60	8.98	54.83	WBD (2008), Kehres and Reinhold (2008)
K2O content [M kg]	21.45	17.18	2.63	WBD (2008), Kehres and Reinhold (2008)
Organic matter [humus equivalent (t TM)-1]	97.09	106.91	33.60	WBD (2008), Kehres and Reinhold (2008)
Quantity applied in agriculture in compost [M t]	0.81	0.89	0.42	Own computations
Nutrient quantity				
N [Euro/kg]	0.74			LEL (2016)
N [Euro/kg]	0.74			LEL (2016)
P2O5 [EUR/kg]	0.82	3.76		LEL (2016)
K2O [EUR/kg]	0.43	1.04		LEL (2016)
Organic matter [EUR/kg]	0.24			Kehres and Reinhold (2008)
Abatement costs				
N value [M Euro]	1.33	1.15	4.97	Own computations
NH4-N value [M Euro]	0.08	0.01	1.37	Own computations
P2O5 value [M Euro]	10.33	7.36	44.96	Own computations
K2O value [M Euro]	9.22	7.39	1.13	Own computations
Organic matter value [M Euro]	23.30	25.66	8.06	Own computations
Total nutrient value [M Euro]	44.27	41.56	60.50	Own computation
	Compost		Sludge	
Marginal abatement costs				
Quantity of compost in agriculture [M t]	1.7		0.42	Own computation
Microplastic concentration [% dry weight]	0.04		0.6	
Microplastic abated from compost and sludge [t]	680		2,520	Own computation
Marginal abatement costs [Eur/kg]	65		24	Own computation

1015

1016

1017 **Appendix A-3.3: Abatement costs – thermal recycling CO2 emissions**

1018 To derive the costs for CO2 emissions, we compute the content of carbon in bio-waste and
1019 sludge and derive the CO2 emissions which are released during the incineration. We consider
1020 these CO2 emissions from incineration as additional emissions, which are released into the
1021 atmosphere, compared to the land-use disposal, as fertilizer, which fixes the carbon in the
1022 soil.
1023

1024 **Table A-3.3.1: Computation of abatement costs for thermal recycling – costs for CO2**
 1025 **emissions from sludge and bio-waste**

	Value	Source
Carbon content and CO2-emissions		
C-content in sludge [% dry weight]	43	Schuchardt and Vorlop (2010)
C-content in bio-waste [% dry weight]	25	Schuchardt and Vorlop (2010)
C-content in sludge [M t]	0.18	Own computation
C-content in bio-waste [M t]	0.20	Own computation
CO2 emissions from sludge [M t]	0.60	Own computation
CO2 emissions from bio-waste [M t]	0.66	Own computation
CO2 price scenarios		
High CO2 price [EUR/CO2eq]	200	Own assumption
Medium CO2 price [EUR/CO2eq]	100	Own definition
Low CO2 price [EUR/CO2eq]	50	Own definition
Emission costs under CO2 price scenarios		
Costs for CO2 from sludge at High CO2 price [M EUR]	120	Own computation
Costs for CO2 from bio-waste at High CO2 price [M EUR]	133	Own computation
Costs for CO2 from sludge at medium CO2 price [M EUR]	60	Own computation
Costs for CO2 from bio-waste at medium CO2 price [M EUR]	66	Own computation
Costs for CO2 from sludge at low CO2 price [M EUR]	30	Own computation
Costs for CO2 from bio-waste at low CO2 price [M EUR]	33	Own computation
Abatement		
Quantity sludge applied in agriculture [M t]	0,42	Own computation
Quantity compost applied in agriculture [M t]	1,7	Own computation
Concentration of microplastic in sludge [%]	0,60	Bertling et al. 2018
Concentration of microplastic in compost [%]	0,04	et al. 2018
Microplastic abatement from sludge [t]	2,520	Own computation
Microplastic abatement from bio-waste [t]	680	Own computation
Marginal abatement costs		
Marginal Abatement Costs for CO2 from sludge at High CO2 price [M EUR]	48.84	Own computation
Marginal Abatement Costs CO2 from bio-waste at High CO2 price [EUR/kg]	195.47	Own computation
Marginal Abatement Costs CO2 from sludge at medium CO2 price [M EUR]	24.42	Own computation
Marginal Abatement Costs CO2 from bio-waste at medium CO2 price [M EUR]	97.74	Own computation
Marginal Abatement Costs CO2 from sludge at low CO2 price [M EUR]	12.21	Own computation
Marginal Abatement Costs CO2 from bio-waste at low CO2 price [M EUR]	48.87	Own computation

1026 **Appendix A-3.4: Abatement costs – filter systems for washing machines**

1027 We base our assumptions to simulate a filter system for reducing microplastic in sewage
 1028 sludge on the system “PlanetCare filters” which filters at a rate of 80% of textile fibres (Stef-
 1029 fen 2019). We assume that such filters are installed in every private washing machine in
 1030 German households and in industrial washing. For the computation of costs we consider only
 1031 the private households.

1032 **Table A-3.4.1: Computation of abatement by filter systems**

Source of microplastic in wastewater	MP before filter	Share of MP	Filter rate	MP with filter	Share with filtering
	g/(cap*year)	[%]	[%]	g/(cap*year)	[%]
Textile fibers	77	57	80	15	11
Cleaning of containers	23	17	0	23	17
Cosmetics	19	14	0	19	14
Abrasive in pipes	12	9	0	12	9
Cleaning products	5	3	0	5	3
Total	135	100	45	74	55

1033

1034

1035 **Table A-3.4.2: Computation of the abatement costs by filter systems**

	Value	Source
Number of washes		
Number of households in Germany in 2015 [M]	40.8	Destatis (2021)
Share of households with washing machine [%]	93.9	Tenzer (2020)
Number of washing machines in households [M]	38.3	Own computation
Number of washes per week (minimum assumption) [# /week]	2	Own assumption
Number of washes per week (minimum assumption) [# /year]	104	Own computation
Number of washes per year (minimum assumption) [M /year]	3.98	Own computation
Costs for filter systems and filters		
Cost for filter system (minimum assumption) [Eur]	35	Steffen (2019)
Cost for filter (minimum assumption) [Eur]	0.8	Steffen (2019)
Lifetime for filter [# of washes]	20	Steffen (2019)
Costs for filter per wash [EUR]	0.04	Own computation
Costs for equipping washing machines with filter systems and filters		
Cost of installing the filter system for each washing machine [M EUR]	1.34	Own computation
Lifetime of filter (own assumption) [# years]	10	Own assumption oriented to the depreciation time for washing machines
Annual cost of installing the filter system [M Euro/year]	134.0	Own computation
Annual costs for filter [M Euro/year]	159.3	Own computation
Annual costs for filter systems and filter [M Euro/year]	293.2	Own computation
Abatement effect and marginal abatement costs		
Sludge applied in agriculture [M t]	0.42	Own computation
Microplastic content in agriculture [%]	0.6	Own computation based on Bertling et al. (2019)
Microplastic from sludge [t]	2,520	Own computation
Abatement effect filtering [%]	45	Own computation based on Steffen A.D. (2019) and Bertling et al (2019)
Abated Microplastic emissions [t]	1,112	Own computation
Marginal Abatement costs for filter system [EUR/kg]	264	Own computation

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1038 **Appendix A-3.5: Abatement costs – detection system**

1039 **A-3.5.1 Estimation of share of bio-waste of total waste**

1040 We estimate the shares of quantities based on the German city Duesseldorf for which the
1041 number of garbage trucks is available. We compute that 20% of the waste collected from
1042 households is bio-waste, 76% is non-recycling waste and 4% is recycling paper.

1043 **Table A-3.5.1: Computation of shares of waste**

	Value	Source
Waste non-recycle [t]	145,388	AWISTA GmbH (2019)
Biowaste in Duesseldorf [t]	39,104	AWISTA GmbH (2019)
Paper recycling [t]	7,339	AWISTA GmbH (2019)
Waste total [t]	191,831	AWISTA GmbH (2019)
Share of waste non-recycle [%]	76	Own computations
Share bio-waste in Duesseldorf [%]	20	Own computations
Share paper recycling [%]	4	Own computations
Share waste total [%]	100	Own computations

1044 **-A-3.5.1 Estimation of the number of garbage trucks used for the collection of bio-waste**

1045 We asked three different institutions for the information on the number of garbage trucks
1046 used for bio-waste collection either for Germany (Federal Motor Transport Authority 2020,
1047 DESTATIS 2020) or at the regional level (LANUV 2020). None of these institutions could
1048 provide data on number of garbage trucks. The survey of single disposal companies or ex-
1049 perts could have provided more information. However, for this study we derived three differ-
1050 ent values for the number of garbage trucks used for bio-waste collection by using three dif-
1051 ferent approaches: (i) based on average bio-waste load in Duesseldorf; (ii) based on the num-
1052 ber of garbage trucks in Germany, and (iii) estimating a value for sensitivity analysis.

1053 (i) Using exemplary values for the German city Duesseldorf we compute, based on the quan-
1054 tities of waste, the share of bio-waste of total waste at 20%. We apply this share to the num-
1055 ber of garbage trucks available for Duesseldorf and compute the annual average load of one
1056 garbage truck. We apply this average load to the whole quantity of bio-waste collected in
1057 Germany and estimate around 1,400 garbage trucks collecting bio-waste in Germany. (ii)
1058 Using the number of total garbage trucks estimated at 12,000 (VAK 2019) we apply the share
1059 computed with (i) at 20% and obtain around 2,500 garbage trucks. (iii) As arbitrary estimator
1060 we define 3,000 garbage trucks for bio-waste collection, which would represent 25% of the
1061 total of 12,000 (VAK 2019).

1062 We use these three derived values as data to estimate the cost for the detection system “DS
1063 2010” (Maier und Fabris GmbH 2021a) by applying the annual costs of 3,950 EUR/garbage
1064 truck (based on Maier 2011). We assume an abatement effect of 90% of reduction of plastic
1065 in bio-waste. This estimation is based on a report on application of the detection system in
1066 different communities or regions in Burgenlandkreis (Otto 2018), Wien Maier (2011),
1067 Euskirchen (Mehren 2015) , Main-Tauber-Kreis (von Brandenstein 2019). For more exam-
1068 ples, see Maier und Fabris GmbH (2021b).

1069 In our costs we do not consider the reduction of costs for the improved quality of the com-
1070 post. Considering this reduction would decrease the abatement cost.

1071

1072 **Table A-3.5.2: Computation of fitted number of garbage trucks for bio-waste collection**
 1073 **with three estimators**

	Value	Source
Estimator 1: Based on average bio-waste load in Duesseldorf		
Total number of garbage trucks in Duesseldorf [#]	55	AWISTA GmbH (2019)
Number of garbage trucks for bio-waste derived by the share of bio-waste (20%) [#]	11	AWISTA GmbH (2019)
Bio-waste in Duesseldorf [t]	39,104	AWISTA GmbH (2019)
Bio-waste per garbage truck in Duesseldorf [t]	3,488	Own computation
Bio-waste in Germany [M t]	4.903	Statistische Ämter des Bundes und der Länder (2019)
Estimated number of garbage trucks collecting bio-waste (computed by Biowaste in Germany / Biowaste per garbage truck in Duesseldorf) [#]	1,400	Own computation
Estimator 2: Based on number of Garbage trucks in Germany		
Number of garbage trucks total in Germany [#]	12,000	VAK (2021)
Share biowaste in Duesseldorf [%]	20	Own computations
Number of garbage trucks for biowaste derived by the share of biowaste (20%) [#]	2,400	Own computation
Estimator 3: Sensitivity Analysis		
Number of garbage trucks for biowaste as sensitivity analysis	3,000	Own assumption

1074 **Table A-3.5.2: Computation of fitted number of garbage trucks for bio-waste collection**
 1075 **with three estimators.**

	Fitted out number of garbage trucks			Source
	Low	Medium	High	
Estimated number of garbage trucks collecting bio-waste	1,400	2,400	3,000	
Cost per day per garbage truck [EUR]	15.19			Maier (2011)
Number of working days (52weeks*5days)	260			Own assumption
Cost for detection system per year and garbage truck [EUR/year]	3,950			Own computation
Cost for detection system per year [M EUR/year]	5.6	9.7	11.9	Own computation
Microplastic from compost [t]	680			Own computation
Reduction by detection system [%]	90			Derived from Otto (2018)
Microplastic abatement [t]	612			Own computation
Marginal abatement costs [EUR/kg]	9.11	15.85	19.43	Own computation

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1078 **Appendix A-4.0: Sensitivity analysis on soil density**

1079 Figure A-4.0 and Table Annex A-4.0 present the microplastic concentrations from sludge and
 1080 compost in soils of different density. The results show that in the years after 2020 the concen-
 1081 trations differ significantly between soils of density of 1.2 g/cm³ and 1.4 g/cm³. The dif-
 1082 ference accounts for sludge for about 7 mg/kg and for compost for about 5 mg/kg. This dif-
 1083 ference increases for consecutive years. The density of light sandy soils on which sludge and
 1084 compost are applied to increase the organic matter can vary from 1.2 to 1.7 g/cm³. Thus, in
 1085 extreme cases, the simulated concentration assuming a soil density of 1.2 g/cm³ can be
 1086 overestimated significant by 30 to 50%.

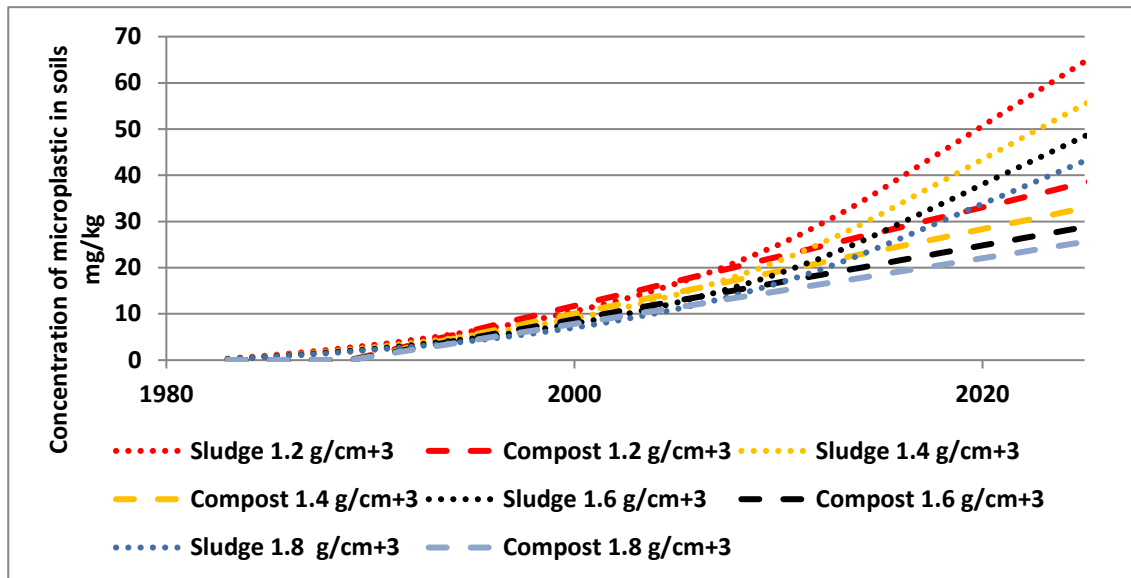


Figure A-4.1: Development of concentration under varied soil density.

Notes: Sludge 1.2 g/cm³ = microplastic from sludge in soils with density of 1.2 g/cm³; sludge 1.4 g/cm³ = microplastic from sludge in soils with density of 1.4 g/cm³; sludge 1.6 g/cm³ = microplastic from sludge in soils with density of 1.6 g/cm³; Sludge 1.8 g/cm³ = microplastic from sludge in soils with density of 1.8 g/cm³; compost 1.2 g/cm³ = microplastic from compost in soils with density of 1.2 g/cm³; compost 1.4 g/cm³ = microplastic from compost in soils with density of 1.4 g/cm³; compost 1.6 g/cm³ = microplastic from compost in soils with density of 1.6 g/cm³; compost 1.8 g/cm³ = microplastic from compost in soils with density of 1.8 g/cm³ by 30 to 50% (see Table A-4.1).

1087

1088

1089 **Table A-4.1: Concentrations simulated for selected year and different soil densities in**
 1090 **mg/kg.**

	Soil density: 1.2 g/cm ³		Soil density: 1.2 g/cm ³		Soil density: 1.2 g/cm ³		Soil density: 1.2 g/cm ³	
	Sludge	Compost	Sludge	Compost	Sludge	Compost	Sludge	Compost
1990	3.2	1.1	2.7	0.9	2.4	0.8	2.1	0.7
1995	6.2	6.4	5.3	5.5	4.7	4.8	4.2	4.3
2000	10.5	11.7	9.0	10.1	7.9	8.8	7.0	7.8
2005	16.5	17.1	14.2	14.6	12.4	12.8	11.0	11.4
2010	25.0	22.4	21.4	19.2	18.7	16.8	16.6	14.9
2015	36.8	27.7	31.5	23.8	27.6	20.8	24.5	18.5
2020	50.7	33.1	43.4	28.3	38.0	24.8	33.8	22.0
2025	64.6	38.4	55.4	32.9	48.5	28.8	43.1	25.6
2030	78.5	43.7	67.3	37.5	58.9	32.8	52.4	29.1
2035	92.5	49.0	79.3	42.0	69.4	36.8	61.7	32.7
2040	106.4	54.4	91.2	46.6	79.8	40.8	70.9	36.3
2045	120.3	59.7	103.1	51.2	90.3	44.8	80.2	39.8
2050	134.3	65.0	115.1	55.7	100.7	48.8	89.5	43.4
2055	148.2	70.4	127.0	60.3	111.1	52.8	98.8	46.9
2060	162.1	75.7	139.0	64.9	121.6	56.8	108.1	50.5

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