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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 $\mu\text{m}$ ,  
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.

$$156 \quad MPCONC_{sludge} = \left( \frac{\sum_{source} MPEM_{source} * POP_{2016}}{Q_{sludge,2016}} \right) * FR \quad (Eq. 1)$$

156 With

157  $MPCONC_{sludge}$  = concentration of microplastics in sewage sludge as % dry weight

158  $MPEM_{source}$ : 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 weight<sup>1</sup> 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.

---

<sup>1</sup>i.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 <sup>a</sup>	1,600	10,000
Medium <sup>b</sup>	600	6,700
Low <sup>c</sup>	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/cm<sup>3</sup> as smallest density for sandy light soils. The choosing the very small density of  
 260 1.2 g/cm<sup>3</sup> results in an overestimation of sandy soils which have higher soil density (e.g., at  
 261 1.4 g/cm<sup>3</sup>), (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 = 10,000m<sup>2</sup>

267 *Ap*: Ploughing horizon = 0.3m

268  $\rho_S$ : Soil density = 1.200 kg/m<sup>3</sup>

### 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 sources<sup>2</sup>.

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.

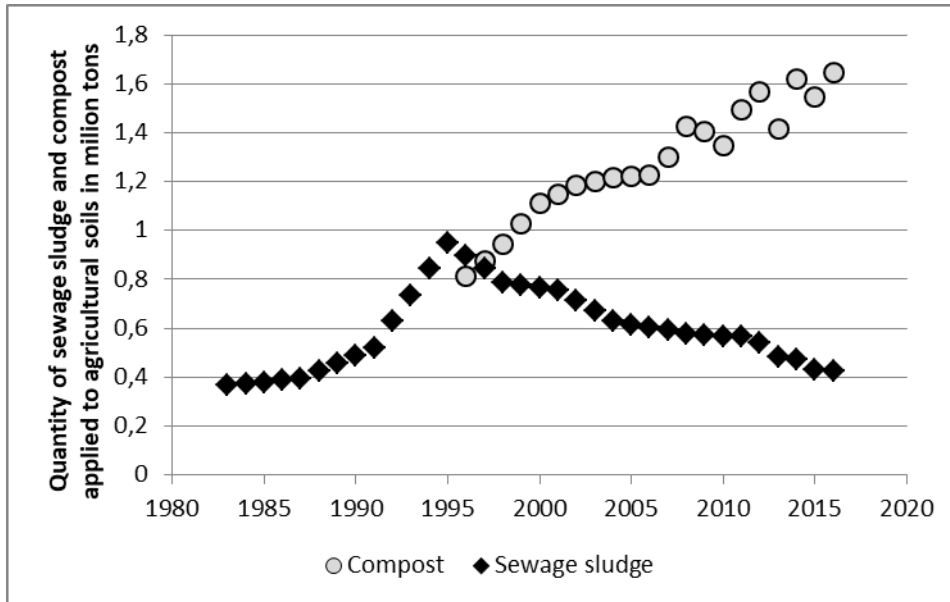
285 The year 1995 saw a peak in the amount of sewage sludge applied and used as fertilizer on  
286 agricultural land, the use has dropped off continuously since then. Changes in disposal capac-  
287 ities and in the demand and use of sewage sludge explain this decreasing trend. The phasing-  
288 out of sewage sludge disposal in landfill sites expanded the capacities of thermal disposal  
289 units (e.g., for incineration)<sup>3</sup> 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.

---

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

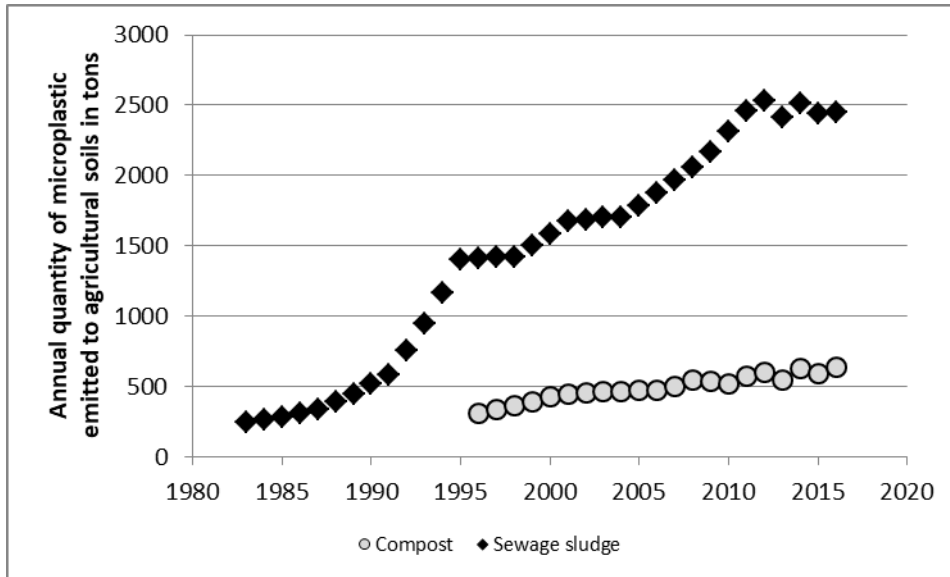
<sup>3</sup>In May 1993 the TASI (Technische Anleitung Siedlungsabfall) prohibited the disposal of organic waste (such as sewage sludge) in landfills (TASI 1993).



**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.

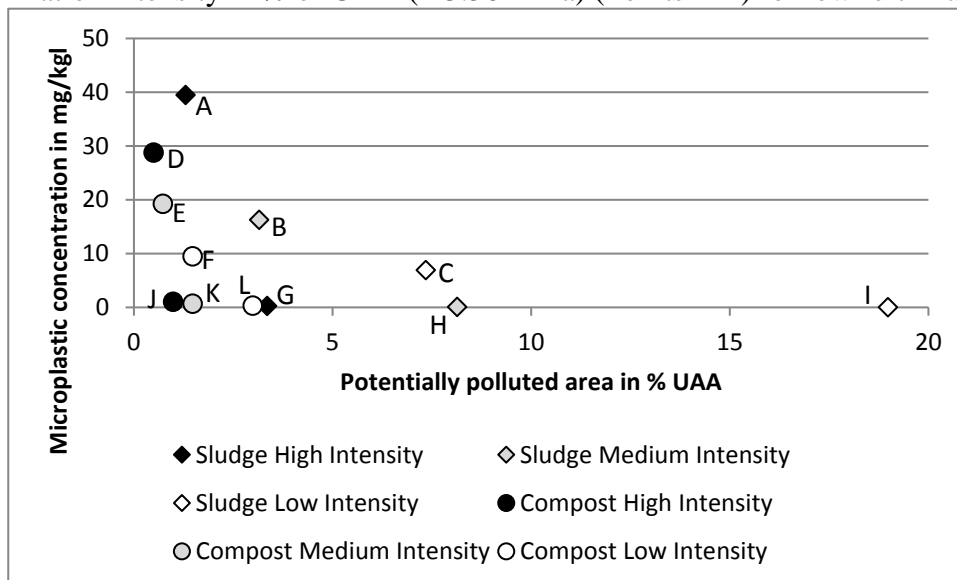
344 We simulate an accumulation of microplastic at 40 mg/kg (Point A) for the fields receiving  
345 an annual application of sludge (for 33 years, between 1983 and 2016), with the highest ferti-  
346 lization intensity. We expect to find this high concentration on a potentially polluted area of  
347 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.**

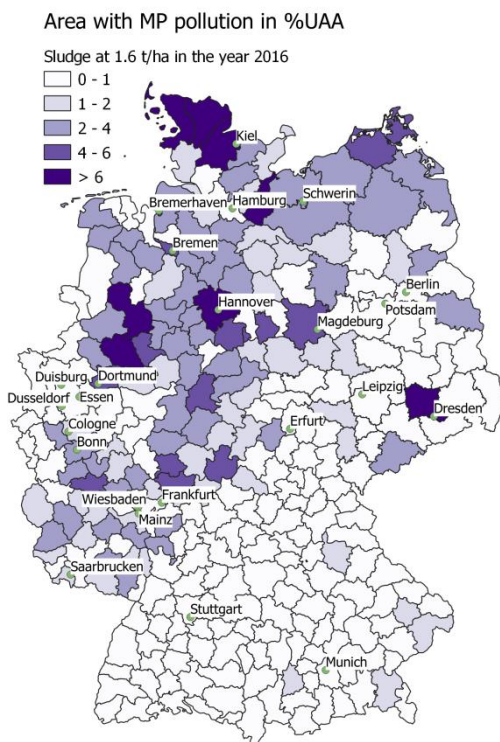
Notes: 1 % of UAA = 0.167 M ha. Scenario assumptions: annual application rates in the: (i) high fertilization intensity scenario: 1.6 t/ha for sludge and 10 t/ha for compost, (ii) medium fertilization intensity scenario: 0.6 t/ha for sludge and 6.7 t/ha for compost. (iii) low fertilization intensity 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/cm<sup>3</sup>. 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.

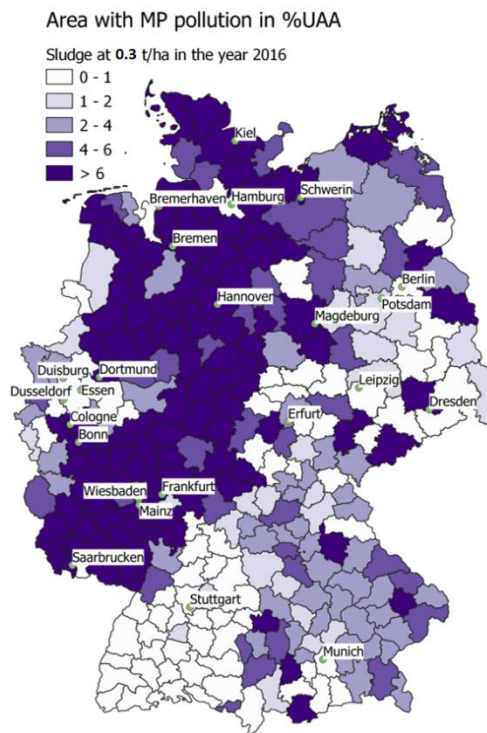
372 In the high fertilization scenario with sludge, the potentially polluted soils reach 1 to 4 % of  
 373 utilized agricultural area (UAA) in the north-western half of Germany, where farmers have  
 374 traditionally been applying more sludge as fertilizer than in the southern regions (Aqua Con-  
 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).

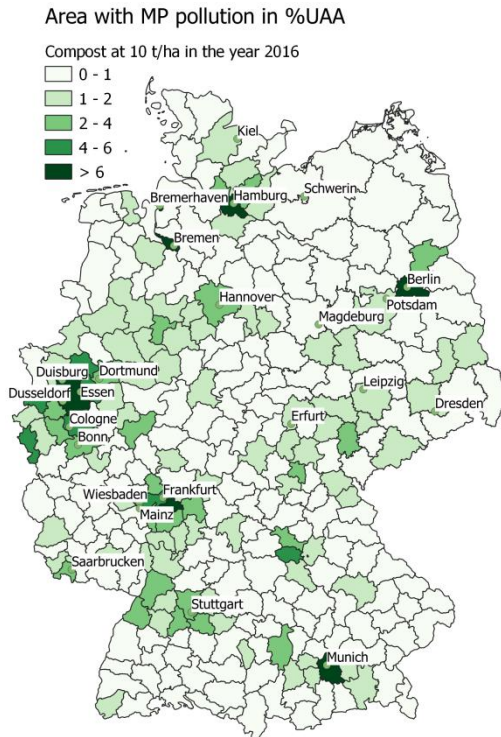
380 In urban regions the polluted area is higher because of high supply of sludge from many in-  
 381 habitants. The low transportation value of sewage sludge limits the transportation distance  
 382 from waste water treatment plants to the sites of application. Consequently, the application of  
 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).



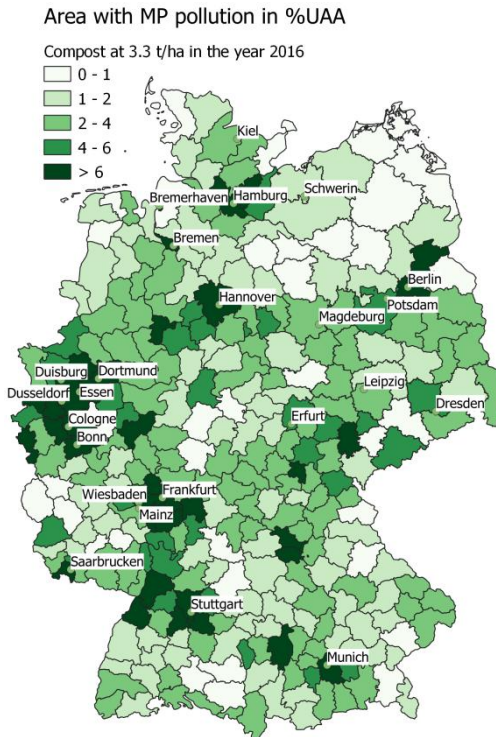
**Fig 4a. Area potentially polluted by microplastic from sludge in share of UAA under fertilization intensity of 1.6 t/ha**



**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 CO<sub>2</sub> 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 CO<sub>2</sub> emissions, we assume that during thermal recycling the carbon in the organic matter is  
 458 burned completely to CO<sub>2</sub>. This CO<sub>2</sub> 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 CO<sub>2</sub>eq.

#### 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
<b>Abatement Reduction rate</b>	100%	45%	100%	80%
<b>Costs</b>				
<b>Cost of tech- nique</b>	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
<b>Cost of Nutri- ent Losses</b>	144 EUR/t		55 EUR/t	
<b>Cost of CO2 emissions</b>	varied for from 0 to 200 EUR/t CO <sub>2</sub> eq		varied for from 0 to 200 EUR/t CO <sub>2</sub> eq	
<b>Projection to 2060</b>				
<b>Quantity of sludge and compost ap- plied to soils</b>	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 CO<sub>2</sub>eq. 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 CO<sub>2</sub>eq (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 <sub>2</sub> eq	[Eur/kg]	110	262	262	262
Thermal recycling, carbon price = 100EUR/t CO <sub>2</sub> eq	[Eur/kg]	85	164	164	164
Thermal recycling, carbon price = 50EUR/t CO <sub>2</sub> 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 <sub>2</sub> eq	[tons]	2450	680	680	680

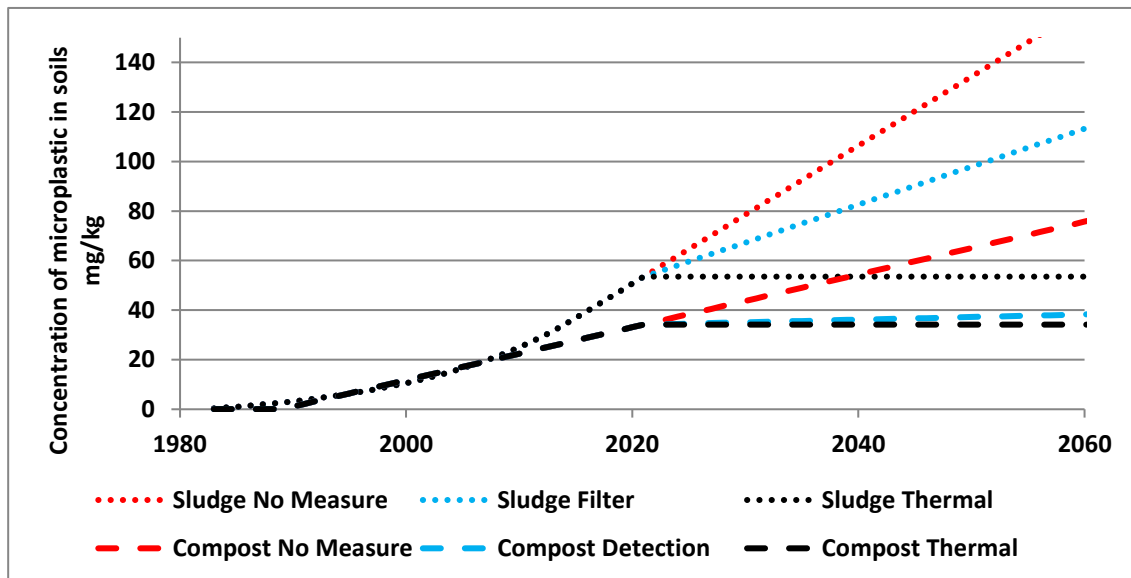
547 For bio-waste, the marginal abatement cost for the garbage truck detection system is cheaper  
 548 than the thermal recycling, even at zero cost emission costs (66 EUR/kg) and even with the  
 549 high assumption of fitting out 3,000 garbage trucks at 19 EUR/kg. The marginal abatements  
 550 costs 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**

624 Abate T.G., Börger T., Aanesen M, Falk-Andersson J, Wyles KJ, Beaumont N. (2020): Valua-  
625 tion of marine plastic pollution in the European Arctic: Applying an  
626 integrated choice and latent variable model to contingent valuation. *Ecological Economics*  
627 169 (2020) 106521

628 AbfKlärV (2017). Verordnung über die Verwertung von Klärschlamm, Klärschlammgemisch  
629 und Klärschlammkompost ( Klärschlammverordnung - AbfKlärV ), 47.

- 630 Aqua Consult Baltic (2015): „Ausarbeitung der Lösungen zur regionalen Klärschlammaufberei-  
 631 tung sowie Ausarbeitung der Kriterien zum Ende der Abfalleigenschaft von Klärschlamm“  
 632 Teil III Begründung. URL: [https://ec.europa.eu/growth/tools-](https://ec.europa.eu/growth/tools-databases/tris/hr/index.cfm/search/?trisaction=search.detail&year=2017&num=154&iLang=DE)  
 633 [databases/tris/hr/index.cfm/search/?trisaction=search.detail&year=2017&num=154&iLang=](https://ec.europa.eu/growth/tools-databases/tris/hr/index.cfm/search/?trisaction=search.detail&year=2017&num=154&iLang=DE)  
 634 [DE](https://ec.europa.eu/growth/tools-databases/tris/hr/index.cfm/search/?trisaction=search.detail&year=2017&num=154&iLang=DE) 2021-02-13
- 635 Backhaus, T., & Wagner, M. (2019). Microplastics in the Environment: Much Ado about  
 636 Nothing? A Debate. *Global Challenges*, 1900022, 1900022.  
 637 <https://doi.org/10.1002/gch2.201900022>
- 638 Bakir, A., Rowland, S. J., & Thompson, R. C. (2014). Enhanced desorption of persistent organic  
 639 pollutants from microplastics under simulated physiological conditions. *Environmental Pollu-*  
 640 *tion*, 185. <https://doi.org/10.1016/j.envpol.2013.10.007>
- 641 Batker D (2020): Implementing ecological economics. *Ecological Economics* 172 (2020)  
 642 106606
- 643 BBodSchG (2017). Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung  
 644 von Altlasten (Bundes-Bodenschutzgesetz - BBodSchG)
- 645 BBodSchV (2017). Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV) BBodSchV
- 646 Bertling, J., Bertling, R., & Hamann, L. (2018). Kunststoffe in der Umwelt : Mikro- und Makro-  
 647 plastik. Ursachen, Mengen, Umweltschicksale, Wirkungen, Lösungsansätze, Empfehlungen.  
 648 Kurzfassung der Konsortialstudie. *Fraunhofer UMSICHT*, 10–11, 16.  
 649 <https://doi.org/10.24406/UMSICHT-N-497117>
- 650 BGK (2017). Verwertung von Bioabfällen 2016. BGK-Statistik . Humuswirtschaft & Kompost  
 651 Aktuell.(Q1 2017 )
- 652 BGK (2018). Kunststoffe in Kompost und Gärprodukten. *Humuswirtschaft & Kompost Aktuell*,  
 653 (Q4 2018).
- 654 BioAbfV (2017). Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich,  
 655 forstwirtschaftlich und gärtnerisch genutzten Böden (Bioabfallverordnung - BioAbfV)
- 656 BKV (2017). *Vom Land ins Meer – Modell zur Erfassung landbasierter Kunststoffabfälle*.
- 657 Bläsing, M., & Amelung, W. (2018). Plastics in soil: Analytical methods and possible sources.  
 658 *Science of the Total Environment*, 612. <https://doi.org/10.1016/j.scitotenv.2017.08.086>
- 659 BMEL (2019). Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten (2019).  
 660 Federal Minister of Food and Agriculture (BMEL). Verbleib von Kompost und Klärschlamm.  
 661 SJT-3060620-0000.xlsx.
- 662 Brennholt, N., Heß, M., & Reifferscheid, G. (2018). Freshwater Microplastics: Challenges for  
 663 Regulation and Management. In Wagner, M., & Lambert, S. (2018). *Freshwater*  
 664 *Microplastics - The Handbook of Environmental Chemistry* 58. [https://doi.org/10.1007/978-](https://doi.org/10.1007/978-3-319-61615-5)  
 665 [3-319-61615-5](https://doi.org/10.1007/978-3-319-61615-5)
- 666 Brodhagen, M., Goldberger, J. R., Hayes, D. G., Inglis, D. A., Marsh, T. L., & Miles, C. (2017).  
 667 Policy considerations for limiting unintended residual plastic in agricultural soils. *Environ-*  
 668 *mental Science and Policy*, 69, 81–84. <https://doi.org/10.1016/j.envsci.2016.12.014>
- 669 Büks, F., van Schaik, N. L., Kaupenjohann, M. (2020). What do we know about how the terres-  
 670 trial multicellular soil fauna reacts to microplastic? SOIL Discuss, in review.  
 671 <https://doi.org/10.5194/soil-2020-4>

- 672 Carney Almroth, B. M., Åström, L., Roslund, S., & Petersson, H. (2017). Quantifying shedding  
673 of synthetic fibers from textiles ; a source of microplastics released into the environment. *En-  
674 viron Sci Pollut Res.* <https://doi.org/https://doi.org/10.1007/s11356-017-0528-7>
- 675 Cesa, F. S., Turra, A., Baruque-Ramos, J. (2017). Synthetic fibers as microplastics in the marine  
676 environment: A review from textile perspective with a focus on domestic washings. *Science  
677 of the Total Environment* 598 (2017) 1116–1129
- 678 Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., & Geissen, V. (2019).  
679 Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal.  
680 *Science of the Total Environment*, 671, 411–420.  
681 <https://doi.org/10.1016/j.scitotenv.2019.03.368>
- 682 Crossman J, Hurley RR, Futter M, Nizzetto L. (2020): Transfer and transport of microplastics  
683 from biosolids to agricultural soils and the wider environment. *Science of The Total Envi-  
684 ronment*, 724, 2020 <https://doi.org/10.1016/j.scitotenv.2020.138334>.
- 685 De Falco, F. , Pia, M., Gentile, G., Di, E., Escudero, R., Villalba, R., ... Avella, M. (2017).  
686 Evaluation of microplastic release caused by textile washing processes of synthetic fabrics \*.  
687 *Environmental Pollution.* <https://doi.org/10.1016/j.envpol.2017.10.057>
- 688 De Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2018).  
689 Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology*, 24(4).  
690 <https://doi.org/10.1111/gcb.14020>
- 691 DüMV (2019). Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen,  
692 Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelverordnung - DüMV)
- 693 DüV (2017). Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursub-  
694 straten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Dün-  
695 gen (Düngeverordnung - DüV)
- 696 Eerkes-Medrano, D., Thompson, R. C., & Aldridge, D. C. (2015). Microplastics in freshwater  
697 systems: A review of the emerging threats, identification of knowledge gaps and prioritisation  
698 of research needs. *Water Research*, 75, 63–82. <https://doi.org/10.1016/j.watres.2015.02.012>
- 699 Espí, E., Salmerón, A., Fontecha, A., García, Y., & Real, A. I. (2006). Plastic films for agricul-  
700 tural applications. *Journal of Plastic Film and Sheeting*, 22(2), 85–102.  
701 <https://doi.org/10.1177/8756087906064220>
- 702 European Commission (2018). Communication from the Commission to the European Parlia-  
703 ment, the Council, the European Economic and Social Committee and the Committee of the  
704 Regions: A European Strategy for Plastics in a Circular Economy. *COM(2018) 28 Final*,  
705 *SWD(2018)(1)*, 1–18. <https://doi.org/10.1021/acs.est.7b02368>
- 706 European Commission (2019): The European Green Deal. Communication by the European  
707 Commision. COM(2019) 640 final. URL: [https://eur-lex.europa.eu/legal-  
708 content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2](https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2) [2021-02-  
709 07]
- 710 European Parliament and the Council of the European Union. (2018). Official Journal of the  
711 European Union L 150: Legislation. *Official Journal of the European Union*, 2018(406), 26–  
712 42. Retrieved from [https://eur-lex.europa.eu/legal-  
713 content/EN/TXT/PDF/?uri=OJ:L:2016:119:FULL](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2016:119:FULL)

- 714 European Union (2012): Consolidated Version of the Treaty on the Functioning of the European  
 715 Union (TFEU) URL: [https://eur-lex.europa.eu/legal-](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN)  
 716 [content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN) [2021-02-07]
- 717 European Union (2020a): EU Action Plan “Towards a Zero Pollution Ambition for air, water  
 718 and soil –building a Healthier Planet for Healthier People”. Communication by the European  
 719 Union. Ref. Ares(2020)5152184 - 01/10/2020 URL:  
 720 [https://ec.europa.eu/environment/strategy/zero-pollution-action-plan\\_en#ecl-inpage-214](https://ec.europa.eu/environment/strategy/zero-pollution-action-plan_en#ecl-inpage-214)  
 721 [2021-02-07]
- 722 European Union (2020b): Circular Economy Action Plan. For a cleaner and more competitive  
 723 Europe. URL: [https://ec.europa.eu/environment/circular-](https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf)  
 724 [economy/pdf/new\\_circular\\_economy\\_action\\_plan.pdf](https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf) [2021-02-25]
- 725 European Union (2021): New Soil Strategy - healthy soil for a healthy life. Communication by  
 726 the European Union. Ref. Ares(2020)6391319 - 05/11/2020. URL:  
 727 [https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12634-New-EU-Soil-](https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12634-New-EU-Soil-Strategy-healthy-soil-for-a-healthy-life)  
 728 [Strategy-healthy-soil-for-a-healthy-life](https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12634-New-EU-Soil-Strategy-healthy-soil-for-a-healthy-life) [2021-02-07]
- 729 Franck, J., & Schröder, L. (2015). Zukunftsfähigkeit kleiner Klärschlammverbrennungsanlagen.  
 730 In J. . Thomé-Kozmiensk &M. . Beckmann (Eds.), *Energie aus Abfall* (Vol. 12, pp. 457–  
 731 476). Verlag KarlThomé-Kozmiensky.
- 732 Gallenkemper, B., & Dohmann, M. (1994). *Klärschlamm-Entsorgung*. Economica-Verlag,  
 733 Bonn.
- 734 Gestoso, I., Cacabelos, E., Ramalhosa, P., & Canning-Clode, J. (2019). Plasticrusts: A new  
 735 potential threat in the Anthropocene’s rocky shores. *Science of the Total Environment*, 687,  
 736 413–415. <https://doi.org/10.1016/j.scitotenv.2019.06.123>
- 737 Gömann, H., Kreins, P., Kunkel, R., & Wendland, F. (2005). Model based impact analysis of  
 738 policy options aiming at reducing diffuse pollution by agriculture - A case study for the river  
 739 Ems and a sub-catchment of the Rhine. *Environmental Modelling and Software*, 20(2), 261–  
 740 271. <https://doi.org/10.1016/j.envsoft.2004.01.004>
- 741 Hagens N.J. (2020): Economics for the future – Beyond the superorganism. *Ecological Econom-*  
 742 *ics* 169 (2020) 106520
- 743 Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., Purnell, P. (2018). An overview of  
 744 chemical additives present in plastics: Migration, release, fate and environmental impact dur-  
 745 ing their use, disposal and recycling. *Journal of Hazardous Materials*, 344, 179-199.  
 746 <https://doi.org/10.1016/j.jhazmat.2017.10.014>
- 747 Henseler, M., Brandes, E., Kreins, P. (2020) Microplastics in agricultural soils: A new challenge  
 748 not only for agro-environmental policy? *Journal of Applied Business and Economics*  
 749 22(7):38-52, DOI:10.33423/jabe.v22i7.3250
- 750 Hernandez, E., Nowack, B., & Mitrano, D. M. (2017). Mechanistic Study to Understand Micro  
 751 fiber Release During Washing. *Environmental Science & Technology*.  
 752 <https://doi.org/10.1021/acs.est.7b01750>
- 753 Herrmann, T., Weiss, V., Bannick, C. G., Ehlers, K., & Claussen, U. (2017). Bioabfallkomposte  
 754 und -gärreste in der Landwirtschaft. *Position*. UBA Position paper
- 755 Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in  
 756 freshwater and terrestrial environments: Evaluating the current understanding to identify the

- 757 knowledge gaps and future research priorities. *Science of the Total Environment*, 586, 127–  
758 141. <https://doi.org/10.1016/j.scitotenv.2017.01.190>
- 759 Huber, A., Bach, M., & Frede, H. G. (2000). Pollution of surface waters with pesticides in  
760 Germany: Modeling non-point source inputs. *Agriculture, Ecosystems and Environment*,  
761 80(3), 191–204. [https://doi.org/10.1016/S0167-8809\(00\)00145-6](https://doi.org/10.1016/S0167-8809(00)00145-6)
- 762 Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salánki, T., Van Der Ploeg, M., ...  
763 Geissen, V. (2016). Microplastics in the Terrestrial Ecosystem: Implications for *Lumbricus*  
764 *terrestris* (Oligochaeta, Lumbricidae). *Environmental Science and Technology*, 50(5), 2685–  
765 2691. <https://doi.org/10.1021/acs.est.5b05478>
- 766 Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M., ...  
767 Geissen, V. (2017). Incorporation of microplastics from litter into burrows of *Lumbricus*  
768 *terrestris*. *Environmental Pollution*, 220, 523–531.  
769 <https://doi.org/10.1016/j.envpol.2016.09.096>
- 770 Hurley, R. R., & Nizzetto, L. (2018). Fate and occurrence of micro(nano)plastics in soils:  
771 Knowledge gaps and possible risks. *Current Opinion in Environmental Science and Health*,  
772 1, 6–11. <https://doi.org/10.1016/j.coesh.2017.10.006>
- 773 Kawecki, D., & Nowack, B. (2019). Polymer-Specific Modeling of the Environmental Emis-  
774 sions of Seven Commodity Plastics As Macro- and Microplastics. *Environmental Science and*  
775 *Technology*, 53(16), 9664–9676. <https://doi.org/10.1021/acs.est.9b02900>
- 776 Kay, P., Hiscoe, R., Moberley, I., Bajic, L., & McKenna, N. (2018). Wastewater treatment  
777 plants as a source of microplastics in river catchments. *Environmental Science and Pollution*  
778 *Research*, 25(20), 20264–20267. <https://doi.org/10.1007/s11356-018-2070-7>
- 779 Kehres, B. (2019). Kunststoffe in Kompost und Gärprodukten Herkunft - Bedeutung - Vermei-  
780 dung. *BGK Information*. Bundesgütegemeinschaft Kompost.
- 781 Knight, L. J., Parker-Jurd, F. N. F., Al-Sid-Cheikh, M., & Thompson, R. C. (2020). Tyre wear  
782 particles: an abundant yet widely unreported microplastic? *Environmental Science and Pollu-  
783 tion Research*. Retrieved from <https://link.springer.com/article/10.1007/s11356-020-08187-4>
- 784 Koelmans, A. A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B. C., ...  
785 Scheffer, M. (2017). Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Be-  
786 lief. *Environmental Science and Technology*, 51(20). <https://doi.org/10.1021/acs.est.7b02219>
- 787 KrWG (2012). Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträg-  
788 lichen Bewirtschaftung von Abfällen: Abfallhierarchie. Retrieved from [https://www.gesetze-  
im-internet.de/krwg/\\_6.html](https://www.gesetze-<br/>789 im-internet.de/krwg/_6.html)
- 790 Kuhn, T., Enders, A., Gaiser, T., Schäfer, D., Srivastava, A. K., & Britz, W. (2020). Coupling  
791 crop and bio-economic farm modelling to evaluate the revised fertilization regulations in  
792 Germany. *Agricultural Systems*, 177(March 2019), 102687.  
793 <https://doi.org/10.1016/j.agsy.2019.102687>
- 794 Kuhn, T., Schäfer, D., Holm-Müller, K., & Britz, W. (2019). On-farm compliance costs with the  
795 EU-Nitrates Directive: A modelling approach for specialized livestock production in north-  
796 west Germany. *Agricultural Systems*, 173(March), 233–243.  
797 <https://doi.org/10.1016/j.agsy.2019.02.017>
- 798 Lahive, E., Walton, A., Horton, A. A., Spurgeon, D. J., & Svendsen, C. (2019). Microplastic  
799 particles reduce reproduction in the terrestrial worm *Enchytraeus crypticus* in a soil exposure.  
800 *Environmental Pollution*, 255, 113174. <https://doi.org/10.1016/j.envpol.2019.113174>



- 801 Lehmann, A., Fitschen, K., & Rillig, M. C. (2019). Abiotic and biotic factors influencing the  
802 effect of microplastic on soil aggregation. *Soil Systems*, 3(1), 1–8.  
803 <https://doi.org/10.3390/soilsystems3010021>
- 804 LfU (Bayerisches Landesamt für Umwelt) 2020: Klärschlamm – Entsorgungssituation. URL:  
805 <https://www.lfu.bayern.de/abfall/klaerschlamm/index.htm>
- 806 Lusher, A., Hollman, P., & Mandoza-Hill, J. . J. (2017). *Microplastics in fisheries and aquacul-*  
807 *ture. FAO Fisheries and Aquaculture Technical Paper* (Vol. 615).  
808 <https://doi.org/dmd.105.006999> [pii]r10.1124/dmd.105.006999
- 809 Marahrens, Stephan; Schmidt, Simone; Frauenstein, Jörg; Mathews, Jeannette; Bussian, Bernd-  
810 Michael; Penn-Bressel, Gertrude; Utermann, Jens; Glante, Frank; Eberhardt, Einar; Frei-  
811 bauer, Annette; Bechthold, Michel; Tiemeyer, Bärbel; Wellbrock, Nicole; Böttch, F. (2015).  
812 *Bodenzustand in Deutschland*. Umweltbundesamt. Retrieved from  
813 [www.umweltbundesamt.de/publikationen/%0Abodenzustand-in-deutschland](http://www.umweltbundesamt.de/publikationen/%0Abodenzustand-in-deutschland)
- 814 Melgar-Melgar, R.E, Hall, C.A.S, (2020): Why ecological economics needs to return to its roots:  
815 The biophysical foundation of socio-economic systems. *Ecological Economics* 169 (2020)  
816 106567
- 817 Ministère de la Transition écologique et solidaire. (2020). Lutte contre la pollution plastique :  
818 Brune Poirson reçoit les fabricants de machines à laver. Communiqué de presse. 17 février  
819 2020. Retrieved from [https://www.ecologique-solidaire.gouv.fr/lutte-contre-pollution-](https://www.ecologique-solidaire.gouv.fr/lutte-contre-pollution-plastique-brune-poirson-recoit-fabricants-machines-laver)  
820 [plastique-brune-poirson-recoit-fabricants-machines-laver](https://www.ecologique-solidaire.gouv.fr/lutte-contre-pollution-plastique-brune-poirson-recoit-fabricants-machines-laver)
- 821 Mintenig, S. M., Int-Veen, I., Löder, M. G. J., Primpke, S., & Gerdts, G. (2017). Identification  
822 of microplastic in effluents of waste water treatment plants using focal plane array-based mi-  
823 cro-Fourier-transform infrared imaging. *Water Research*, 108, 365–372.  
824 <https://doi.org/10.1016/j.watres.2016.11.015>
- 825 Möller, J. N., Löder, M. G. J., & Laforsch, C. (2020). Finding Microplastics in Soils: A Review  
826 of Analytical Methods. *Environmental Science and Technology*, 54(4), 2078–2090.  
827 <https://doi.org/10.1021/acs.est.9b04618>
- 828 Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from  
829 domestic washing machines : Effects of fabric type and washing conditions. *Marine Pollution*  
830 *Bulletin*. <https://doi.org/10.1016/j.marpolbul.2016.09.025>
- 831 Ng, E., Huerta, E., Eldridge, S. M., Johnston, P., Hu, H., Geissen, V., & Chen, D. (2018). An  
832 overview of microplastic and nanoplastic pollution in agroecosystems. *Science of the Total*  
833 *Environment*, 627, 1377–1388. <https://doi.org/10.1016/j.scitotenv.2018.01.341>
- 834 Nizzetto, L., Bussi, G., Futter, M. N., Butterfield, D., & Whitehead, P. G. (2016). A theoretical  
835 assessment of microplastic transport in river catchments and their retention by soils and river  
836 sediments. *Environ. Sci.: Processes Impacts*, 18(8), 1050–1059.  
837 <https://doi.org/10.1039/C6EM00206D>
- 838 Okoffo ED, Tschärke BJ, O'Brien JW, O'Brien S, Ribeiro F, Burrows SD, Choi PM, Wang X,  
839 Mueller JF, Thomas KV. Release of Plastics to Australian Land from Biosolids End-Use.  
840 *Environ Sci Technol*. 2020 Dec 1;54(23):15132-15141. doi: 10.1021/acs.est.0c05867. Epub  
841 2020 Nov 17. PMID: 33200922.
- 842 Pirc, U., Vidmar, M., Mozer, A., & Kržan, A. (2016). Emissions of microplastic fibers from  
843 microfibre fleece during domestic washing. *Environmental Science and Pollution Research*,  
844 23(21), 22206–22211. <https://doi.org/10.1007/s11356-016-7703-0>

- 845 Rillig, M. C., Ingraffia, R., & de Souza Machado, A. A. (2017). Microplastic Incorporation into  
846 Soil in Agroecosystems. *Frontiers in Plant Science*, 8(October), 8–11.  
847 <https://doi.org/10.3389/fpls.2017.01805>
- 848 Rillig, M.C., Lehmann, A., Ryo, M., Bergmann, J. (2019). Shaping Up: Toward Considering the  
849 Shape and Form of Pollutants. *Environmental Science & Technology* 53(14), 7925-7926.  
850 <https://doi.org/10.1021/acs.est.9b03520>
- 851 Rodriguez-Seijo, A., Lourenço, J., Rocha-Santos, T. A. P., da Costa, J., Duarte, A. C., Vala, H.,  
852 & Pereira, R. (2017). Histopathological and molecular effects of microplastics in *Eisenia an-*  
853 *drei Bouché*. *Environmental Pollution*, 220, 495–503.  
854 <https://doi.org/10.1016/j.envpol.2016.09.092>
- 855 Roskosch, A., & Heidecke, P. (2018). *Klärschlamm Entsorgung in der Bundesrepublik Deutsch-*  
856 *land*.
- 857 SAPEA (2019). *A Scientific Perspective on Microplastics in Nature and Society*. SAPEA,  
858 Science Advice for Policy by European Academies. Berlin.  
859 <https://doi.org/10.26356/microplastics>
- 860 Sattler, C., Kächele, H., & Verch, G. (2007). Assessing the intensity of pesticide use in agricul-  
861 ture. *Agriculture, Ecosystems and Environment*, 119(3–4), 299–304.  
862 <https://doi.org/10.1016/j.agee.2006.07.017>
- 863 Selonen, S., Dolar, A., Jemec Kokalj, A., Skalar, T., Parramon Dolcet, L., Hurley, R., & van  
864 Gestel, C. A. M. (2020). Exploring the impacts of plastics in soil – The effects of polyester  
865 textile fibers on soil invertebrates. *Science of the Total Environment*, 700.  
866 <https://doi.org/10.1016/j.scitotenv.2019.134451>
- 867 Scientific Advisory Board on Fertiliser Issues at the Federal Ministry of Food and Agriculture.  
868 (2015). *Application of Organic Fertilisers and Organic Residual Materials in Agriculture*.  
869 Retrieved from  
870 [https://www.bmel.de/SharedDocs/Downloads/EN/Ministry/AppOrganicFertilisersOrganicRes-](https://www.bmel.de/SharedDocs/Downloads/EN/Ministry/AppOrganicFertilisersOrganicResidualMaterialsAgriculture.pdf?__blob=publicationFile)  
871 [idualMaterialsAgriculture.pdf?\\_\\_blob=publicationFile](https://www.bmel.de/SharedDocs/Downloads/EN/Ministry/AppOrganicFertilisersOrganicResidualMaterialsAgriculture.pdf?__blob=publicationFile)
- 872 Shi, J., Sanganyado, E., Wang, L., Li, P., Li, X., Liu, W. (2020). Organic pollutants in sedimen-  
873 tary microplastics from eastern Guangdong: Spatial distribution and source identification.  
874 *Ecotoxicology and Environmental Safety*, 193. <https://doi.org/10.1016/j.ecoenv.2020.110356>.
- 875 Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C., & Gieré, R. (2018). Tire  
876 abrasion as a major source of microplastics in the environment. *Aerosol and Air Quality Re-*  
877 *search*, 18(8), 2014–2028. <https://doi.org/10.4209/aaqr.2018.03.0099>
- 878 StaLA-BW (Statistischen Landesamt Baden-Württemberg). 2021: Landwirtschaftliche Klär-  
879 schlammverwertung ist die Ausnahme -- Baden-Württemberg: In der Mehrzahl der Kreise  
880 wurde der gesamte Klärschlamm verbrannt (Statistischen Landesamt Baden-Württemberg  
881 (StaLaBW). Pressemitteilung 8/2021. URI: [http://www.statistik-](http://www.statistik-bw.de/Presse/Pressemitteilungen/2021008)  
882 [bw.de/Presse/Pressemitteilungen/2021008](http://www.statistik-bw.de/Presse/Pressemitteilungen/2021008)
- 883 Statista (2019). Polyester fiber production globally 1975-2017. Uploaded by Garside M., Aug  
884 15, 2019. Retrieved from [https://www.statista.com/statistics/912301/polyester-fiber-](https://www.statista.com/statistics/912301/polyester-fiber-production-worldwide/)  
885 [production-worldwide/](https://www.statista.com/statistics/912301/polyester-fiber-production-worldwide/)
- 886 Statistisches Bundesamt and DWA-Arbeitsgruppe KEK-1.2 “Statistik.” (2015). Abwasser und  
887 Klärschlamm in Deutschland – statistische Betrachtungen Teil 2: Klärschlamm, Klärgas, Re-  
888 chen und Sandfanggut. *Korrespondenz Abwasser, Abfall*, 62(1). Retrieved from  
889 <https://www.destatis.de/DE/Themen/Gesellschaft->

- 890 Umwelt/Umwelt/Wasserwirtschaft/Publikationen/Downloads-Wasserwirtschaft/abwasser-  
891 klaerschamm-5322102159004.pdf?\_\_blob=publicationFile&v=5
- 892 Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 “Statistik.” (2014). Abwasser und  
893 Klärschlamm in Deutschland – statistische Betrachtungen Teil 1: Abwasserbehandlung. *Kor-*  
894 *respondenz Abwasser, Abfall*, 61(12). Retrieved from  
895 <https://www.destatis.de/DE/Themen/Gesellschaft->  
896 [Umwelt/Umwelt/Wasserwirtschaft/Publikationen/Downloads-Wasserwirtschaft/abwasser-](https://www.destatis.de/DE/Themen/Gesellschaft-)  
897 [klaerschamm-5322102159004.pdf?\\_\\_blob=publicationFile&v=5](https://www.destatis.de/DE/Themen/Gesellschaft-)
- 898 Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., ... Schaumann,  
899 G. E. (2016). Plastic mulching in agriculture. Trading short-term agronomic benefits for long-  
900 term soil degradation? *Science of the Total Environment*, 550, 690–705.  
901 <https://doi.org/10.1016/j.scitotenv.2016.01.153>
- 902 TASI (1993). Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von  
903 Siedlungsabfällen, 1–65. Retrieved from <https://www.umwelt->  
904 [online.de/recht/abfall/ta\\_siedl/taa\\_ges.htm](https://www.umwelt-)
- 905 UBA (2020). Bioabfälle. Data-Set: An Bioabfallbehandlungsanlagen angelieferte biologisch  
906 abbaubare Abfälle. Umweltbundesamt (UBA). Based on: Statistisches Bundesamt (2019):  
907 Abfälle. Fachserie 19 Umwelt, R. 1 Abfallentsorgung, verschiedene Jahrgänge; Abfallentsor-  
908 gung . Retrieved from <https://www.umweltbundesamt.de/bild/an->  
909 [bioabfallbehandlungsanlagen-angelieferte](https://www.umweltbundesamt.de/bild/an-)
- 910 UM-BW (Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg) (2021):  
911 Entsorgung – Klärschlämme. <https://um.baden-wuerttemberg.de/de/umwelt-natur/abfall-und->  
912 [kreislaufwirtschaft/abfallstroeme/abfallarten-und-ihre-entsorgung/klaerschlaemme/](https://um.baden-wuerttemberg.de/de/umwelt-natur/abfall-und-)
- 913 VAK (2021): Refuse collection vehicles - Environment and safety details make the difference.  
914 Verband der Arbeitsgeräte- und Kommunalfahrzeug-Industrie e.V. (VAK). URL:  
915 <https://www.vak-ev.de/en/members/refuse-collection-vehicles> [2021-02-21]
- 916 Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., ...  
917 Georg, R. (2014). Microplastics in freshwater ecosystems : what we know and what we need  
918 to know. *Environmental Sciences Europe 2014*, 26:12, 26(12), 1–9.  
919 <https://doi.org/10.1186/s12302-014-0012-7>
- 920 Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., & Zhang, P. (2019). Science of the  
921 Total Environment Microplastics as contaminants in the soil environment : A mini-review.  
922 *Science of the Total Environment*, 691, 848–857.  
923 <https://doi.org/10.1016/j.scitotenv.2019.07.209>
- 924 Weithmann, N., Möller, J. N., Löder, M. G. J., Piehl, S., Laforsch, C., & Freitag, R. (2018).  
925 Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Science Ad-*  
926 *vances*, 4(4), 1–18. <https://doi.org/10.1126/sciadv.aap8060>
- 927 Weller, S., Fischer, A., Willibald, G., Navé, B., & Kiese, R. (2019). N2O emissions from maize  
928 production in South-West Germany and evaluation of N2O mitigation potential under single  
929 and combined inhibitor application. *Agriculture, Ecosystems and Environment*, 269(February  
930 2018), 215–223. <https://doi.org/10.1016/j.agee.2018.10.004>
- 931 Wijesekara, H., Bolan, N. S., Bradney, L., Obadamudalige, N., Seshadri, B., Kunhikrishnan, A.,  
932 ... Vithanage, M. (2018). Trace element dynamics of biosolids-derived microbeads. *Chemo-*  
933 *sphere*, 199, 331–339. <https://doi.org/10.1016/j.chemosphere.2018.01.166>

- 934 Zambrano, M. C., Pawlak, J. J., Daystar, J., Ankeny, M., & Cheng, J. J. (2019). Microfibers  
935 generated from the laundering of cotton , rayon and polyester based fabrics and their aquatic  
936 biodegradation Micro fi bers generated from the laundering of cotton , rayon and polyester  
937 based fabrics and their aquatic biodegradation. *Marine Pollution Bulletin*, 142(May), 394–  
938 407. <https://doi.org/10.1016/j.marpolbul.2019.02.062>
- 939 Zubris, K. A. V., & Richards, B. K. (2005). Synthetic fibers as an indicator of land application  
940 of sludge. *Environmental Pollution*, 138(2), 201–211.  
941 <https://doi.org/10.1016/j.envpol.2005.04.013>  
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943 **Microplastic pollution in agricultural soils and abatement measures – a model-based**  
 944 **assessment for Germany**

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**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

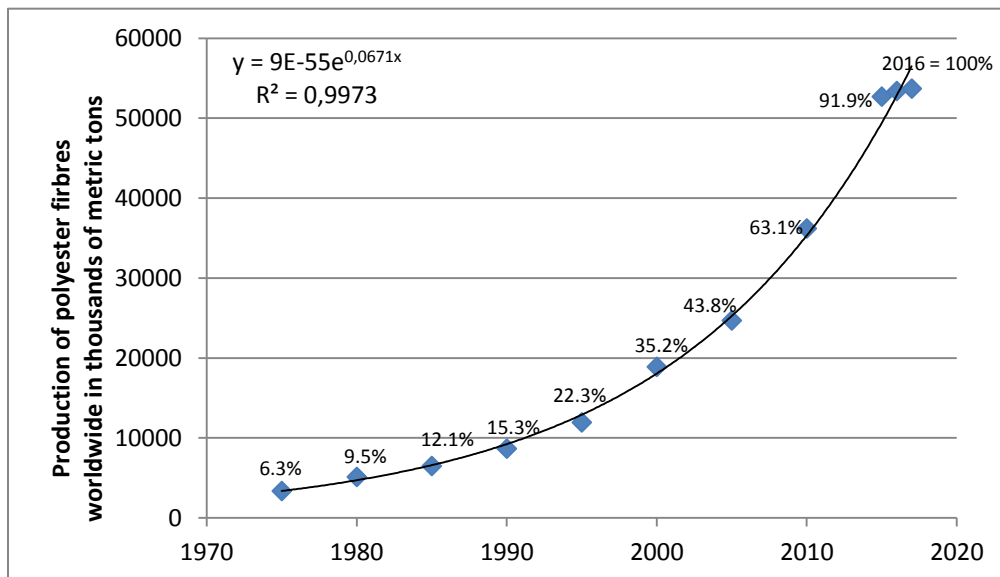
959 53 million tons in 2016 (Fig.1). We fit an exponential model to describe the evolution of the

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.



964 **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)**

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., CO<sub>2</sub> 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 <sup>a)</sup>
<b>Thermal recycling</b>			
Costs for incineration [EUR/kg]		0.44	1.07
Losses of nutrients [EUR/kg]		24	65
Costs for CO <sub>2</sub> 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
<b>Filter System</b>			
Cost for filter system and replacement [EUR/kg]		264	
<b>Detection system</b>			
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
<b>Abatement costs</b>		
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
<b>Abatement</b>		
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
<b>Marginal abatement costs</b>		
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
<b>Abatement costs</b>		
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
<b>Abatement</b>		
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
<b>Marginal abatement costs</b>		
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
<b>Nutrient quantity</b>				
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
<b>Nutrient quantity</b>				
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)
<b>Abatement costs</b>				
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
	<b>Compost</b>		<b>Sludge</b>	
<b>Marginal abatement costs</b>				
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

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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 CO<sub>2</sub>**  
 1025 **emissions from sludge and bio-waste**

	Value	Source
<b>Carbon content and CO<sub>2</sub>-emissions</b>		
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
CO <sub>2</sub> emissions from sludge [M t]	0.60	Own computation
CO <sub>2</sub> emissions from bio-waste [M t]	0.66	Own computation
<b>CO<sub>2</sub> price scenarios</b>		
High CO <sub>2</sub> price [EUR/CO <sub>2</sub> eq]	200	Own assumption
Medium CO <sub>2</sub> price [EUR/CO <sub>2</sub> eq]	100	Own definition
Low CO <sub>2</sub> price [EUR/CO <sub>2</sub> eq]	50	Own definition
<b>Emission costs under CO<sub>2</sub> price scenarios</b>		
Costs for CO <sub>2</sub> from sludge at High CO <sub>2</sub> price [M EUR]	120	Own computation
Costs for CO <sub>2</sub> from bio-waste at High CO <sub>2</sub> price [M EUR]	133	Own computation
Costs for CO <sub>2</sub> from sludge at medium CO <sub>2</sub> price [M EUR]	60	Own computation
Costs for CO <sub>2</sub> from bio-waste at medium CO <sub>2</sub> price [M EUR]	66	Own computation
Costs for CO <sub>2</sub> from sludge at low CO <sub>2</sub> price [M EUR]	30	Own computation
Costs for CO <sub>2</sub> from bio-waste at low CO <sub>2</sub> price [M EUR]	33	Own computation
<b>Abatement</b>		
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
<b>Marginal abatement costs</b>		
Marginal Abatement Costs for CO <sub>2</sub> from sludge at High CO <sub>2</sub> price [M EUR]	48.84	Own computation
Marginal Abatement Costs CO <sub>2</sub> from bio-waste at High CO <sub>2</sub> price [EUR/kg]	195.47	Own computation
Marginal Abatement Costs CO <sub>2</sub> from sludge at medium CO <sub>2</sub> price [M EUR]	24.42	Own computation
Marginal Abatement Costs CO <sub>2</sub> from bio-waste at medium CO <sub>2</sub> price [M EUR]	97.74	Own computation
Marginal Abatement Costs CO <sub>2</sub> from sludge at low CO <sub>2</sub> price [M EUR]	12.21	Own computation
Marginal Abatement Costs CO <sub>2</sub> from bio-waste at low CO <sub>2</sub> 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	<b>11</b>
Cleaning of containers	23	17	0	23	<b>17</b>
Cosmetics	19	14	0	19	<b>14</b>
Abrasive in pipes	12	9	0	12	<b>9</b>
Cleaning products	5	3	0	5	<b>3</b>
<b>Total</b>	135	100	45	74	55

1033

1034

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

	<b>Value</b>	<b>Source</b>
<b>Number of washes</b>		
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
<b>Costs for filter systems and filters</b>		
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
<b>Costs for equipping washing machines with filter systems and filters</b>		
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
<b>Abatement effect and marginal abatement costs</b>		
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
<b>Estimator 1: Based on average bio-waste load in Duesseldorf</b>		
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
<b>Estimator 2: Based on number of Garbage trucks in Germany</b>		
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
<b>Estimator 3: Sensitivity Analysis</b>		
Number of garbage trucks for biowaste as sensitivity analysis	3,000	Own assumption

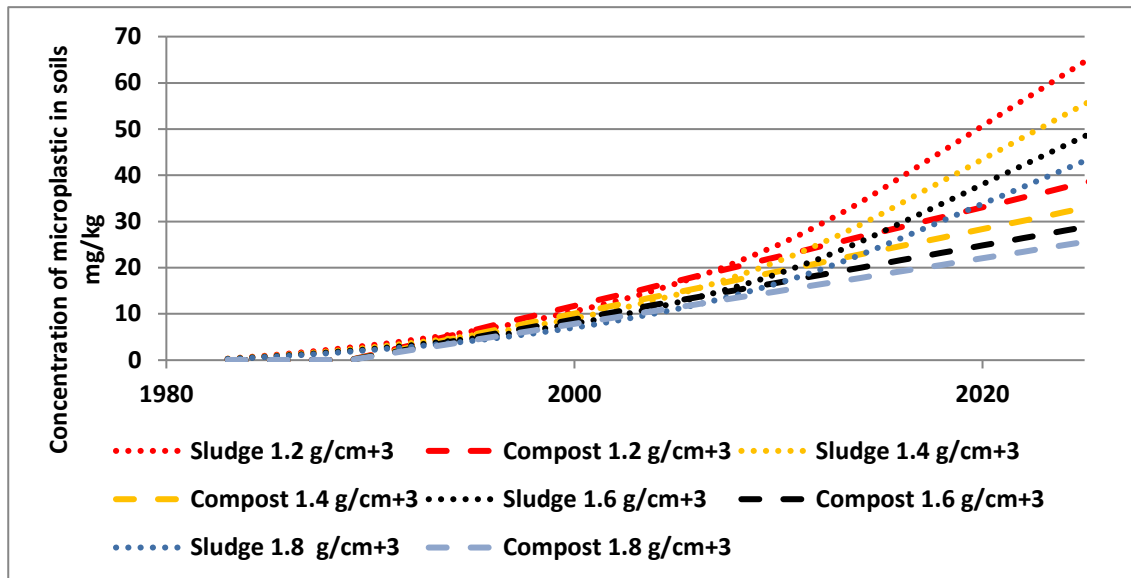
1074 **Table A-3.5.2: Computation of fitted number of garbage trucks for bio-waste collection**  
 1075 **with three estimators.**

	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/cm<sup>3</sup> and 1.4 g/cm<sup>3</sup>. 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/cm<sup>3</sup>. Thus, in  
 1085 extreme cases, the simulated concentration assuming a soil density of 1.2 g/cm<sup>3</sup> 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/cm<sup>3</sup> = microplastic from sludge in soils with density of 1.2 g/cm<sup>3</sup>; sludge 1.4 g/cm<sup>3</sup> = microplastic from sludge in soils with density of 1.4 g/cm<sup>3</sup>; sludge 1.6 g/cm<sup>3</sup> = microplastic from sludge in soils with density of 1.6 g/cm<sup>3</sup>; Sludge 1.8 g/cm<sup>3</sup> = microplastic from sludge in soils with density of 1.8 g/cm<sup>3</sup>; compost 1.2 g/cm<sup>3</sup> = microplastic from compost in soils with density of 1.2 g/cm<sup>3</sup>; compost 1.4 g/cm<sup>3</sup> = microplastic from compost in soils with density of 1.4 g/cm<sup>3</sup>; compost 1.6 g/cm<sup>3</sup> = microplastic from compost in soils with density of 1.6 g/cm<sup>3</sup>; compost 1.8 g/cm<sup>3</sup> = microplastic from compost in soils with density of 1.8 g/cm<sup>3</sup> by 30 to 50% (see Table A-4.1).

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

	Soil density: 1.2 g/cm <sup>3</sup>		Soil density: 1.2 g/cm <sup>3</sup>		Soil density: 1.2 g/cm <sup>3</sup>		Soil density: 1.2 g/cm <sup>3</sup>	
	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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1093 **Literature -- Appendix**

- 1094 AWISTA GmbH (2019): Düsseldorf bleibt sauber. Buisness report of the AWISTA GmbH  
 1095 2018. URL: [https://www.awista.de/wp-](https://www.awista.de/wp-content/uploads/2019/08/Gesch%C3%A4ftsbericht-2018.pdf)  
 1096 [content/uploads/2019/08/Gesch%C3%A4ftsbericht-2018.pdf](https://www.awista.de/wp-content/uploads/2019/08/Gesch%C3%A4ftsbericht-2018.pdf)
- 1097 DESTATIS (2020): Anzahl Mülltransportwagen in D \_ Statistisches Bundesamt, GZ 465555  
 1098 \_ 668635. Personal communication via email with Erxleben, C. date: 27.10.2020
- 1099 Destatis (2021): Haushalte und Familien -- Daten zur Entwicklung der Zahl der Privathaushalte nach Haushaltsgröße für die Jahre 2015 bis 2035  
 1100
- 1101 Entwicklung der Zahl der Privathaushalte nach Haushaltsgröße bis 2035 (Trendvariante)  
 1102 Deutschland. Statistisches Bundesamt (Destatis). Stand 28. Februar 2017
- 1103 Federal Motor Transport Authority 2020: AW: Statistiken\_Verkehr\_deutscher\_Lastkraftfahrzeuge // AZ: 321-130/10476-20. Personal communication via email with Schleunes E. date 12.11.2020.  
 1104  
 1105  
 1106 [https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Haushalte-](https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Haushalte-Familien/Tabellen/vorausberechnung-haushalte.html)  
 1107 [Familien/Tabellen/vorausberechnung-haushalte.html](https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Haushalte-Familien/Tabellen/vorausberechnung-haushalte.html) [2021-02-21]
- 1108 Kehres B, Reinhold J (2008): Monetäre Bewertung der Humusreproduktion von Kompost  
 1109 und Gärrückständen. H&K 2/08, 20 ff,
- 1110 LANUV (2020) WG Anzahl der landesweiten Anzahl der Mülltransportwagen für Biomüll -  
 1111 'Holst, Heike' (Heike.Holst@lanuv.nrw.de) - 2020-11-18 1131. Personal communication via email with Holst, H. date: 18.11.2020  
 1112
- 1113 LEL (2016): Düngerpreis P, Vers. 2.4 11/2. LEL Schwäbisch Gmünd.
- 1114 Maier HJ (2011): Die Kommunen sollten mehr tun für den Klimaschutz. Die Bürger sparen  
 1115 dabei noch Müll-Gebühren! September 2019/ UmweltJournal-Wien. Page 11. URL:  
 1116 <https://www.maier-fabris.de/images/Umwelt-Journal-Wien-09-2019.pdf>
- 1117 Maier und Fabris GmbH (2021a): Detection System " DS 2010 " (Product description). URL:  
 1118 <https://www.maier-fabris.de/images/Prosp-0519-2-engl.pdf>[2021-02-22]
- 1119 Maier und Fabris GmbH (2021b). Homepage Maier and Fabris GmbH.  
 1120 [URL:https://www.maier-fabris.de/pages/frame\\_produkt.htm](https://www.maier-fabris.de/pages/frame_produkt.htm) [021-02-22]
- 1121 Mehren L (2015): Erfahrungsbericht über den Einsatz des Detektionssystems im Landkreis  
 1122 Euskirchen. URL: [https://www.maier-fabris.de/images/Vortrag\\_Euskirchen\\_2015.pdf](https://www.maier-fabris.de/images/Vortrag_Euskirchen_2015.pdf)
- 1123 Otto H. (2018): "Aktion Biotonne" im Burgenlandkreis: Maßnahmen zur Fremdstoffreduzierung. Presentation. URL: [https://www.maier-fabris.de/images/Erfahrungsbericht-](https://www.maier-fabris.de/images/Erfahrungsbericht-Burgenlandkreis.pdf)  
 1124 [Burgenlandkreis.pdf](https://www.maier-fabris.de/images/Erfahrungsbericht-Burgenlandkreis.pdf),  
 1125
- 1126 Schuchardt F., Vorlop K-D (2010): Abschätzung des Aufkommens an Kohlenstoff in Biomasse-Reststoffen in Deutschland für eine Verwertung über Hydrothermale  
 1127 Carbonisierung (HTC) und Einbringung von HTC-Kohle in den Boden.  
 1128 Landbauforschung - vTI Agriculture and Forestry Research 4 2010 (60) 205-212. URL:  
 1129 <https://d-nb.info/1009077295/34>  
 1130
- 1131 Statistische Ämter des Bundes und der Länder (2019): Aufkommen an Haushaltsabfällen.  
 1132 Statistikportal. URL: <https://www.statistikportal.de/de/aufkommen-haushaltsabfaellen>
- 1133 Steffen A.D. (2019): This Is The First Ever Microplastics Filter For Washing Machines!  
 1134 [www.intelligentliving.co](https://www.intelligentliving.co). URL: [https://www.intelligentliving.co/microplastics-filter-](https://www.intelligentliving.co/microplastics-filter-washing-machines/)  
 1135 [washing-machines/](https://www.intelligentliving.co/microplastics-filter-washing-machines/) [2021-02-21]

- 1136 Tenzer F. (2020): Anteil der privaten Haushalte in Deutschland mit Waschmaschine bis 2020.  
1137 Pulished by Tenzer, F. (10.11.2020) on www. Statista.com. URL:  
1138 [https://de.statista.com/statistik/daten/studie/516859/umfrage/private-haushalte-in-](https://de.statista.com/statistik/daten/studie/516859/umfrage/private-haushalte-in-deutschland-mit-waschmaschine/)  
1139 [deutschland-mit-waschmaschine/](https://de.statista.com/statistik/daten/studie/516859/umfrage/private-haushalte-in-deutschland-mit-waschmaschine/) [2021-02-21]
- 1140 VAK (2021): Refuse collection vehicles - Environment and safety details make the differ-  
1141 ence. Verband der Arbeitsgeräte- und Kommunalfahrzeug-Industrie e.V. (VAK). URL:  
1142 <https://www.vak-ev.de/en/members/refuse-collection-vehicles> [2021-02-21]
- 1143 von Brandenstein, H (2019): Biomüll-Qualität ist deutlich gestiegen. Fränkische Nachrichten.  
1144 Samstag15.JUNI2019/Seite17. URL: [https://www.maier-](https://www.maier-fabris.de/images/FraenkischeNachrichten15062019.pdf)  
1145 [fabris.de/images/FraenkischeNachrichten15062019.pdf](https://www.maier-fabris.de/images/FraenkischeNachrichten15062019.pdf)
- 1146 WBD (2015): Application of Organic Fertilisers and Organic Residual Materials in Agricul-  
1147 ture Position paper of the Scientific Advisory Board on Fertiliser Issues. Scientific Advi-  
1148 sory Board on Fertiliser Issues at the Federal Ministry of Food and Agriculture (WBD):  
1149 s:24/25; Tabelle A1