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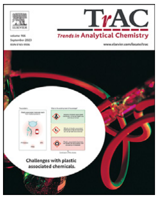

Fate of microplastics in sewage sludge and in agricultural soils

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ABSTRACT

The aim of this study was to review microplastics (MPs) occurrence in sewage sludge from wastewater treatment plants (WWTPs) and assess implications of sludge application to agricultural soils.

Sludge is a main sink for MPs in WWTPs, highlighting the importance of sludge as a route for environmental exposure. Sludge application on agricultural fields is associated with elevated MP concentrations in soils, potentially affecting soil health. However, prior to application sludge treatments may alter MP abundance and MPs properties, such as shape and size, subsequently affecting environmental risk.

Knowledge gaps still exist regarding sludge treatments and their effect on MPs (size, shape abundance). Further investigation is needed to assess the risk of MPs exposure at WWTPs, explore the effects of sludge treatments on soil health, and to better understand how management at WWTPs, and in agricultural systems, affect MP properties.

1. The importance of investigating MPs in sludge

Sewage sludge (hereafter sludge) used as fertilizer on agricultural fields has been identified as an important pathway of microplastics (MPs) to soils which is an area of growing concern [1]. Yet current studies that illuminate both MP abundance in sludge, and the role of sludge treatment processes in altering or removing MPs are still scarce [2]. Recently, several studies have addressed different aspects of this topic, providing a strong foundation for a more holistic review. Gao et al. [3] provided insight into the sources, prevalence, and treatment of MPs in wastewater treatment plants (WWTPs), whereas Cydzik-Kwiatkowska et al. [4] reviewed the effects of different sludge treatment technologies on removing MPs from sludge. Finally, Christian and Köper [5] published a review of the ecological impacts of MPs present in biosolids (sludge applied as fertilizer). This review provides additional insight by linking these aspects and discussing the implications of treatment technologies, ecological contamination, and impact on soil health from a holistic perspective.

It is suggested that the practice of applying sludge to agricultural land creates one of the largest global reservoirs of MP pollution within the soils [6]. Comparative studies have shown that MP concentrations were 2.3–2.8 times higher on soils amended with sewage sludge compared to untreated soils [7]. Other studies estimated that biosolids could introduce 7.2×10^{12} to 1.5×10^{14} MP particles per year to agricultural fields [8]. As a result, sludge application to soils have been associated with elevated MP contents, generally increasing with the number of applications [7,9–11], suggesting an accumulative effect.

Despite limited information regarding size, shape, and polymer types within sludge [12], MP concentrations may cause changes in soil ecosystems and soil structure. Here the number of MPs in sludge are potentially influenced by geographical, temporal, and methodological differences [13]. It is estimated that up to 99% of MPs at WWTPs are retained in sludge, creating a potential route for environmental exposure through agricultural application [2,6–8], further emphasizing the need to remove MPs from sludge fraction before it reaches the soil.

At the same time, global assessments suggest that most productive soils are lacking organic matter [14]. Currently there is a critical nutrient imbalance in agricultural systems where nutrients are removed as crops to urban areas [15,16]. A recirculation of nutrients back into farming systems by sludge applications to soil might counteract this imbalance, returning nutrients from urban

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centers back to rural ecosystems [4,17]. An example of the importance of sludge as fertilizer is the content of phosphorous (P), which is a finite resource crucial for plant production [18]. Sludge is considered as the third biggest source of P in Danish agriculture [17], emphasizing the importance of sludge as a potential resource for recirculating P and other nutrients. Additionally, biosolids are an inexpensive source of organic matter for agricultural soils that can simultaneously help improving soil structure and soil health [15], the latter being defined as “the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems” [16]. However, sludge from urban areas inevitably contains undesired contaminants, including MPs. Thus, it is essential to improve our understanding of how sludge treatments may both affect nutrient content and the abundance of MPs.

For sludge to be used as biosolids, several treatment steps are necessary to reduce water content in the sludge fraction at the WWTP. This involves dehydration, thickening and stabilization processes, all of which may influence MP abundance, size, and surface morphology [19] in the post-treated sludge product leaving the WWTP [20]. Conversely, MPs may also affect sludge treatment processes. For instance, the presence of MPs in sludge slowed and thereby worsened biomass settling properties of sludge during the treatment [4]. The settling properties of the solid fraction are critical for an efficient removal of water from the sludge (dewatering). Hence, understanding MP characteristics and quantities in the sludge fraction is an essential step towards minimizing uncertainties related to MP effects on sludge and soils, after application. Subsequent treatment procedures may play an essential role in altering or removing MPs from the sludge before its categorization as biosolids. Therefore, understanding how sludge treatments can affect MP abundance and properties becomes crucial to minimize the potential risk of environmental exposure.

The aim of this review is twofold: 1) to assess WWTP sludge MP concentrations and properties (Fig. 1 – Focus 1) while 2) including the environmental fate and impact of MPs in biosolids administered from the actual WWTPs to agricultural fields (Fig. 1 – Focus 2). This includes concentrations of MPs in different sludges in response to treatment methods and the current understanding of MPs in soils after sludge application, with focus on MPs size, shape, type, and potential ecological implications [5]. Implications of different management practices on the fate of MPs and the impact of MP pollution on soil health are also addressed. While we acknowledge that MPs-associated chemicals, (i.e., additives and sorbed/adhered contaminants) and other components associated with sludge (e.g. metals) may have significant impacts on the soil health, it is beyond the scope of this review and is only discussed briefly in section 3.2.

2. MPs at WWTPs – concentrations and the environmental exposure

Generally, treatments at WWTPs consist of various steps, often including an initial bar and grit screening of the wastewater, followed by sedimentation in settling tanks, and separation of the solid (sludge) from the liquid phase. The view on sludge has changed over the years, at first considered a waste product but now considered as a resource [4]. However, the primary goal of WWTPs is still to improve the water quality of the effluent. After separation of solid and liquid fraction, a combination of sludge treatments can be applied to the solid sludge fraction prior to application on soil [21,22].

At this stage, sludge treatment techniques may be a key driver for altering or reducing MPs in sludge. Knowledge about the behavior of MPs within WWTPs and how treatment affects MPs can help identify major internal sinks and potential techniques to achieve MP reduction in the final biosolid product. For instance, a central part of sludge treatments is dewatering. During this process it is necessary to use an emulsion polymer, which can affect MP concentrations in sludge [23]. Reject water from the dewatering process is typically recycled back into the wastewater stream at WWTP, which can cause a reintroduction of MPs of up to 20% [24]. Once MPs are reintroduced into the wastewater stream, they become harder to remove, therefore it would be advantageous to further investigate how to hinder these reintroductions. Thus, highlighting current management processes, which are not accounting for the risk of continued re-contamination of MPs within WWTPs.

2.1. Distribution of MPs in WWTP

The central entry point of MPs to the WWTPs is inlet to the plants [25]. Once MPs have entered the WWTP, the majority accumulates in the sludge fraction, while a much smaller fraction is released to the environment through the discharge water [26]. MPs are primarily removed from the water phase during the settling of the solid phase in a series of connected settling tanks [27,28]. This is in part caused by the strong affinity of MPs to bind with organic matter [29]. One study that assessed the distribution of MPs within a Swedish WWTP found that 66% of the smaller MP particles ($\leq$500 μm) were retained within the sludge fraction [25]. This is especially problematic for the soil application, since smaller particles can pose a higher ecological risk [3]. In a comparable study, 84% of the MPs entering the WWTP (2.5 ± 0.3 MP L^{-1}) were removed from the effluent, meaning MPs were instead enriched in the solid sludge fraction with concentrations of 113 ± 57 MP g^{-1} (Dry weight) DW [30]. Another study from a Spanish WWTP found similar concentrations in the sludge fraction with 165 ± 37 MP g^{-1} DW [29]. In contrast, a study from Taiwan found markedly lower concentrations of 1 and 7 MP g^{-1} in sludge [31], suggesting that regional differences might influence the MP distribution within WWTPs.

2.2. Methodological uncertainties in MPs detection

To date, no standardized method has been adopted for the sampling and analysis of MPs in wastewater or sludge. Generally, MP extraction from sludge includes density separation and an impurity removal step. Specific chemicals, reagents and enzymes used differ between studies [32]. However, the applied sampling methodology, sample preparation steps, and analytical techniques can strongly impact the ability to quantify and characterize MPs, such as the captured polymer types, sizes and abundances [5].

Therefore, it can be argued that the differences observed in MP concentrations at WWTPs may, in part, be attributed to different sampling methodologies and analytical techniques [33,34]. In addition, sample timing may influence the outcome of the analysis due to daily and seasonal variations in inlet concentrations at WWTPs and the high heterogeneity of sludge [5]. Thus, sampling should be conducted at different timepoints to account for temporal variations [35]. Comparative studies are needed that focus specifically on sludge treatments, to ensure the observed variation between treatments in different studies is not due to methodological uncertainties.

Another major challenge for MP analysis in sludge is the removal of organic matter, which can interfere with the identification of MPs [28]. However, some of the applied organic matter removal steps can alter MPs. For instance, acids have strongly degrading effects on various plastics [28]. Even the use of hydrogen peroxide (H_2O_2, generally 30%), which is considered more conservative and the most widely applied method, can shrink and increase the

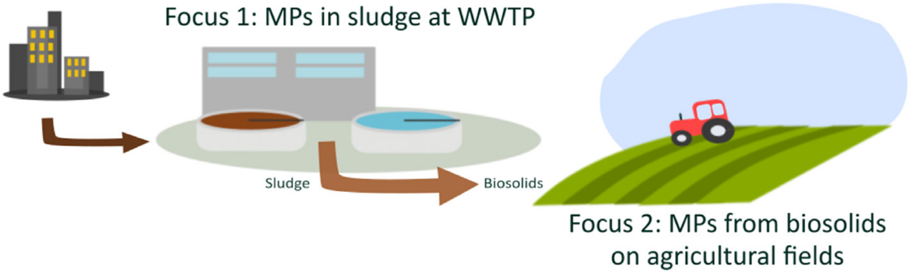

Fig. 1. Overview of the flow of microplastics (MPs) from society through the wastewater treatment plants (WWTPs) and onto agricultural fields. Illustrating objective of the paper. The brown arrow from sludge to biosolids indicates sludge treatments, since sludge is categorized as biosolids after sludge treatments. The focus is on 1. MPs at WWTPs and 2. The environmental implications when using sludge fractions from WWTPs as biosolids on agricultural fields. Upstream solutions and implications before WWTPs will not be addressed in this paper.

transparency of some MPs [36]. Its degrading effect on polyamides (PA) may be problematic in particular [36], as it is one of the dominant plastic polymers found in WWTPs [24,37]. The inherent risk of degrading MPs during sample treatments is a potential underestimation or misinterpretation of MP concentrations in samples.

Since sludge treatments can fragment and shear MPs [19,38], applied sampling and analysis methods should consider how to capture and analyze the smaller sized MPs to avoid underestimation of overall plastic loads. For instance, sieves (≥20 μm) used to sample wastewater omit the smallest plastic fraction [33]. In conjunction with difficulties in capturing the smaller sized MPs through sampling, there are also technical limitations during final analysis. Commonly used for MP characterization and quantification are Fourier Transform Infrared (FT-IR) and Raman spectroscopy [36]. Raman spectroscopy can capture smaller particles (≥1 μm) in contrast to FT-IR (≥20 μm). As a result, studies directly comparing these two methods on the same sample have found that FT-IR analysis tends to underestimate MP numbers in comparison to Raman spectroscopy by up to approximately 35% [20]. However, Raman spectroscopy has a longer detection timespan, potentially offsetting its advantage in detecting lower size ranges [28].

The limitations of the analytical instruments, combined with effects of extraction methods on MPs, could result in MP underestimation, which is an evident concern [19] where inconsistencies among methodologies pose a challenge when attempting to compare results from different WWTPs. The issue of harmonization and scientific consensus on best practice should be addressed in the future [36].

2.3. Effects of sludge treatments on MPs at WWTPs

Gaining an understanding of how different sludge treatments affect MPs in sludge can be considered a gateway to minimizing risks of MPs in soils. In one study, MP abundance ranged from 4196 to 15 385 particles kg^{-1} across different sludge treatments at seven different WWTPs [19] with a high degree of variation between results. Sludge composition and MP content is greatly influenced by the input wastewater and type of WWTP, which can vary greatly between geographical locations [13,39,40]. This emphasizes the necessity for including pre-treatment sludge samples in future studies to accurately determine the cause of variation between treatments from different locations.

Several studies which currently compare different sludge treatments only investigate the sludge post-treatment [19]. This merely provides an indication of MPs in the final sludge product, indicating MP concentrations contributed to agricultural soils, and not the effects of sludge treatments on MP abundance.

However, it is not merely MP concentrations which pose an ecological risk in soil, but rather both MPs size and shape [3–5]. A rougher morphology and smaller size can increase the environmental risk of the particles in the soil (Section 3.2) and affect transport in terrestrial environment (Section 3.1). Some sludge treatments can fragment and shear MPs, resulting in reduced size of MP (≤500 μm) (Table 1) [19,38], which can subsequently influence soil health (Section 3.2), and create implications when analyzing MP abundance (section 2.2).

Therefore, assessing different sludge treatments helps to gain a better understanding of the most efficient removal methods (Fig. 2), while also gaining a better understanding of the properties of the remaining MPs (Table 1), including their potential effect when applied to soils (section 3) [19,38].

Fig. 2 provides an overview of assessed sludge treatments and their effect on abundance. The following provides further elaboration on sludge treatments and their effects on MPs properties.

2.3.1. Anaerobic digestion

Anaerobic digestion is done to stabilize and recover methane from sludge [42]. Some studies found that anaerobic digestion could potentially reduce MP abundance compared to other treatments [19,24]. Contrary, another study found no significant change in MP abundance between pre- and post-treatment in mesophilic anaerobic digestion, possibly due to a high variation within samples. A lower post-treatment concentration could be a result of fragmentation, thus reducing the number of particles in the identified size range, although this needs further research [43].

Several studies indicate that the efficiency of reducing MP concentrations by anaerobic digestion might be polymer-dependent and that the decrease in MP concentrations is primarily related to polylactic acid (PLA) and polyhydroxybutyrate (PHB) [24], which are considered technically biodegradable plastics. However, even though PLA can be degraded by up to 90% in an anaerobic digestion reactor at a retention time of 60 days, the typical WWTP retention time is only 15-30 days [24]. This highlights the potential role of management in the efficiency of MP removal through anaerobic digestion. Aside from effects on particle numbers, anaerobic digestion has been found to increase surface roughness, potentially increasing adsorption of contaminants [4], which might add another risk factor for subsequent application to soil.

2.3.2. Lime stabilization

Lime can be added to raw sludge to raise the pH [44] which decreases the pathogenic content and accessibility of metals, thereby reducing environmental risks while enhancing agricultural benefits [45]. However, a study found that lime stabilization might shear MPs and lead to successive fragmentation, possibly due to increased pH and mechanical mixing [19], which could have

Table 1
Overview of how sludge treatments are affecting properties of microplastics (MPs). A "—" indicates insufficient data in the scientific literature. This table is a summary of information included in this review to provide an overview of the differences between sludge treatments in regard to their influence on MP concentrations, size and shape.

	Concentration of MPs	Size of MPs	Shape of MPs
Dewatering	Potential increase with emulsion polymer [23]	-	-
Anaerobic digestion	Potential reduction [19,24]	Potential fragmentation [43]	Change surface morphology [4]
Thermal processes	Reduction [3,4,19,38,41]	Potential fragmentation [38]	Changed surface morphology [41] Tear and protrusions [4] Melt and blister [19]
Lime stabilization	-	Shear MPs [19]	-

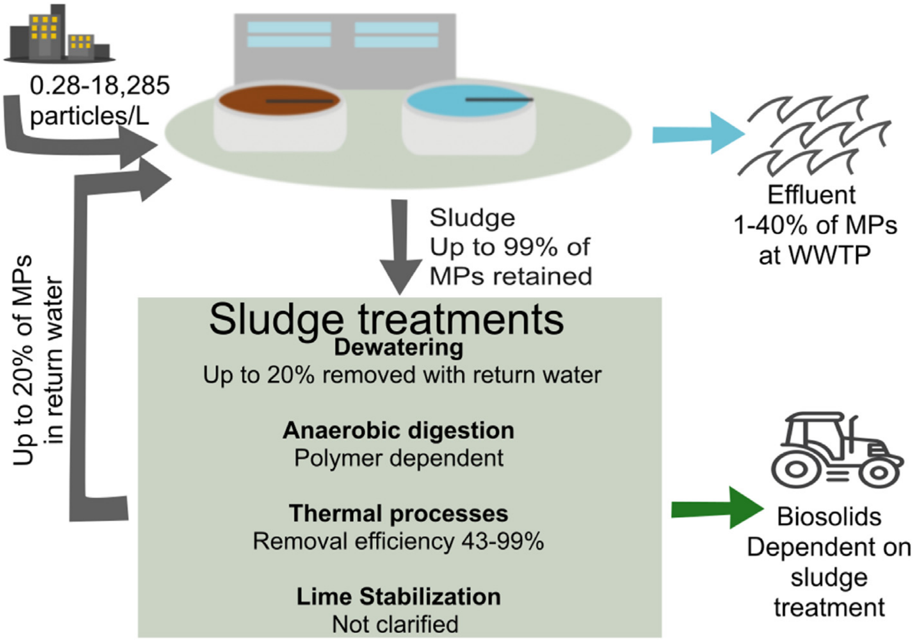

Fig. 2. Visualization of microplastics (MPs) concentrations in different steps revolving sludge. An example of influent concentrations [3], the accumulation of MPs in sludge [2,6–8]. Emphasized on the sludge treatments removal efficiency of MPs (dewatering [24], Anaerobic digestion [4], thermal processes [3,4,19,38,41] and lime stabilization [19]). Percentages indicate how much MPs are reduced in sludge fraction. Percentages outside of sludge treatment box explain how much of original MP concentration are introduced to WWTPs [24], aquatic [28] or terrestrial environment.

implications for soil application.

2.3.3. Thermochemical processing of sewage sludge

Sludge can be treated thermochemically, through oxidative or non-oxidative heating, to reduce its solid content or make recalcitrant carbon more biodegradable. Thermochemical processes have the technical capacity to convert biomass to gas, which is then used as an energy supply through chemical and physical transformations [42,46,47].

Thermochemical processes can reduce, melt and blister MPs [19]. For pyrolysis, the exact temperature setting (400–800 °C) is important for the thermal degradation of MPs [41]. One study demonstrated that MP abundance decreased significantly (by 99.7%) at temperatures above 450 °C [41]. At temperatures under 450 °C the surface roughness of MPs increased, which could result in higher adsorption of contaminants if the pyrolysis of the MPs is incomplete [41]. Hydrothermal Carbonization (HTC) can also reduce the abundance of MPs up to 79% [38]. Apart from fully degrading the MPs, HTC resulted in a significant reduction of MP particle size. For example, before HTC 14.9% of the particles were >500 μm, whereas after HTC at 260 °C no MPs particles >500 μm were detected [38]. Considering the relatively low temperature (260 °C), these findings could also indicate a fragmentation at a size below detection limit rather than degradation, which poses a greater risk in the soil with smaller polymer size. Again, implications of methodology are highlighted.

It is apparent that sludge treatments have different impacts on MP abundance and properties such as shape, size and surface morphology (Table 1). Thermal processes appear to have the highest removal efficiency for MPs. Conversely, thermal treatments alter the sludge fraction the most with potential consequences their applicability to soil and soil health. In addition, the specific conditions of the treatment such as temperature or duration can moderate the treatment effects on MPs. Incomplete removal but enhanced degradation might, for instance, increase surface roughness and particle number which in turn may enhance potential adsorption of contaminants to MP particles and their subsequent risk to the soil environment. It is therefore important to not merely focus on the sludge treatment with the highest removal efficiency, but also investigate how these new biosolids are affecting soil health. Few comparative studies have investigated this link.

3. What are environmental implications of MPs for agricultural fields?

It is critical to understand the ecological risks of biosolids since these can affect both soil heath, soil organisms, and crop responses (Section 3.2). The load of MPs within biosolids applied to fields are affected by sludge treatments [6,19], population equivalence, as well as socio-economic and infrastructural conditions of the source area [13]. Additionally, reported concentrations in biosolid-amended soils vary between case studies, ranging from 546 particles kg^{-1} after one application to 10 400 particles kg^{-1} after five applications [48], highlighting the accumulative effect. Current results indicate that MP contamination of soils follows as an unintended consequence of using sludge as fertilizer. This contamination is a global problem: estimates of MPs annually entering soils through biosolids in Europe range from 63 000 to 430 000 metric tons [49], and an estimated 1.56×10^{14} MP particles are released to the environment each year from Chinese WWTPs [13]. The wide range in MP concentrations observed in agricultural fields amended with biosolids are proposedly due to initial loadings in the sludge but may also be due to the wide array of extraction and identification methods used for quantification and associated limitations and uncertainties, as well as fate processes altering local MP levels [32] (Section 2.2 and 2.3).

3.1. Environmental fate

Once MPs are applied with biosolids to soil, their potential negative effect on the soil environment depends on their local distribution and residence time that are altered by their transport and degradation behaviour (Fig. 3). As highlighted before, size and shape of MPs are affected by sludge treatments (Table 1), which in turn may determine their subsequent mobility and ecological risk in soil. Despite this, little research focuses on the impact of different sludge treatments on the biosolids product and their further impact on soil environment. The following implications and effects are therefore based on the overall effects of biosolids on MP concentrations in soils, as well as effects of several of the MP properties such as shape and size, presented in Table 1 on soil environment.

3.1.1. Transport processes for MPs

MP content in biosolid amended soils are typically highest in the topsoil layers, often corresponding to the depth of ploughing or seedbed preparation [1,10]. Consequently, it is likely that crops are directly exposed to MPs added with biosolids. However, MPs can be transported by wind [50,51] and water via surface run off [9,52] (Fig. 3), from the initial biosolid application site to other soils [1] or other ecosystems [11]. Some field studies have observed retention of MPs in soils even after biosolid applications have ceased [1,9]. In contrast, other field and modelling approaches suggest 60-90% of the total MPs from biosolids may be exported from soils with runoff [11,53]. Arguably, soil type, climate, landscape properties, and application conditions of the biosolids which influence transport processes for other particulates may be important for MP fate.

In contrast, MPs may also be incorporated deeper into the soil profile through ploughing [1], bioturbation and ingestion from burrowing soil biota [54,55], or transport with infiltrating water [52]. Soil processes that enhance macropore structures (Fig. 3) tend to promote vertical MP transport [56,57]. In addition, MP properties directly affect their transport dynamics, including shapes, sizes, plastic type and surface charge. On agricultural fields, MPs have been detected down to 0.9–2 m, with smaller MPs generally recorded to penetrate to greater depths [38,58]. Process-studies have shown that higher density MPs are preferentially transported downward in soil profile in contrast to lower density MPs [56], and spheres more than fragments in another study [56]. Hence, physico-chemical changes of MPs due to sludge treatments may directly affect their mobility in the soil, affecting larger areas of the terrestrial ecosystem.

3.1.2. Degradation

Incorporating MPs into the soil affect long-term residence time as some decisive abiotic degradation processes (e.g. photodegradation) are inhibited below the soil surface [59,60]. Plastic degradation in soil is directly or indirectly mediated by temperature [61], pH, and moisture content which govern hydrolysis reactions [59,62], as well as oxygen and nutrient availability. These environmental factors can affect microbial and enzymatic activity and thereby the potential biodegradation and biotic assimilation of MPs [62]. Microbial and enzymatic activity may also be affected by the biosolids themselves (pH, organic matter, other contaminants) or by the pre-treatment of the sludge through promoting biofilm formation. Such effects of sludge treatments on the degradation of MPs in soil is still poorly understood and requires further investigation.

Expected degradation rates of most plastics are generally low in the soil environment, evidenced by the legacy plastics found in soils with a past of biosolid application [1,9]. Estimated degradation times range from several years to several thousand years [59], although there are uncertainties as testing protocols differ among studies [63]. Even bio-degradable polymers, such as PLA, may take several years to biodegrade in soils depending on the prevalent conditions [64]. Consequently, MPs applied to soils with biosolids are expected to accumulate within the soil, becoming a long-lasting component of the soil environment [1,65]. While MPs are affected by the local soil conditions, their presence may conversely affect the soil environment [66].

3.2. Environmental impact of MPs

MPs effects on soil health are complex, with direct and indirect effects that can differ based on plastic type, particle size and shape, as well as soil properties and the specific endpoint considered [64,65,67]. The presence of MPs can alter physico-chemical properties of the soil, such as soil structure, bulk density, permeability, water retention capacity, aeration, microporosity, rooting and nutrient immobilization [5,28,65,66,68]. These changes can affect soil biota and plants, though the direction of the effect is not straightforward. For instance, MP presence has been associated with negative, positive, and no effects on plant biomass [65,66]. Changes in root traits, germination, and above ground biomass have been observed for a range of plant species [15,65,67,69,70].

Both anaerobic digestion and thermal processes can fragment and change the morphology of MPs, thus increasing MPs potential to act as a vector (section 2.3). Co-exposure experiments of MPs with metals that are commonly associated with biosolids, such as copper and cadmium, showed enhanced metal accumulation in earthworms [71]. However, this trend was opposite for arsenic and for some hydrophobic organic contaminants, due to irreversible adsorption of the contaminants [71]. Notably, these contaminants also interact with the non-synthetic organic matter of biosolids, often serving as feed for soil organisms. Therefore, the relative contribution of MPs as vectors for such contaminants remains to be evaluated. Yet another dimension of complexity is added if the potential effects of degradation products of MPs are included. The effect of degradation products on soil organisms are largely dependent on the specific chemical composition of the material including the content and type of additives (anti-oxidants, plasticizers, flame-retardants, UV-stabilizers), which can make up to 70% of the total plastic weight [72]. A better understanding of the long-

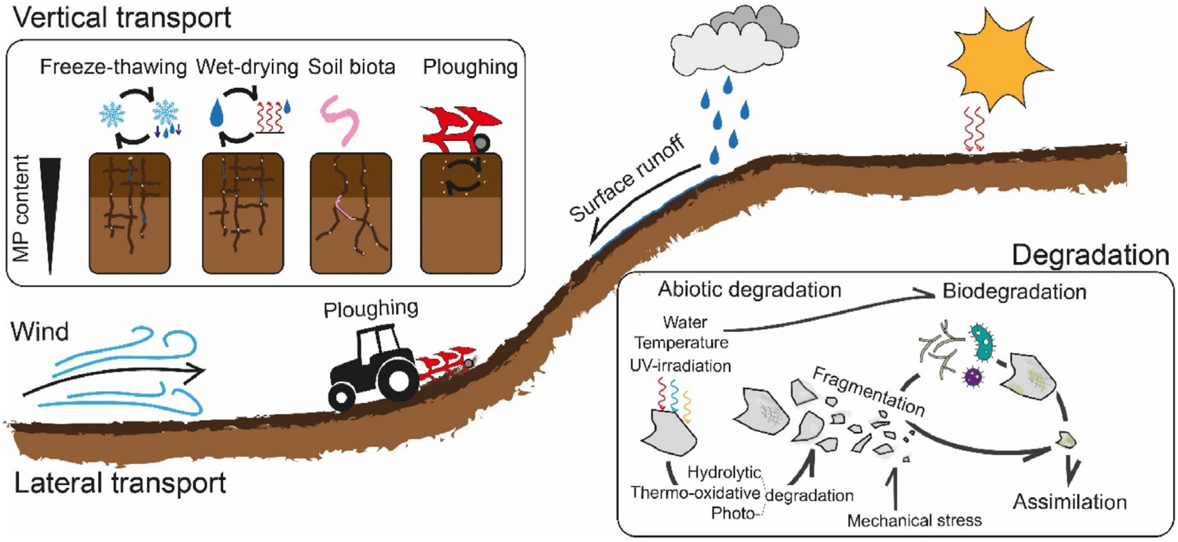

Fig. 3. Fate processes of microplastics (MPs) after biosolid application to agricultural fields, including vertical and horizontal transport processes, and general processes relevant for the potential degradation of plastics.

term degradation of MPs from biosolids in soils is needed to assess this additional exposure pathway.

Adverse impacts on the soil environment are likely to occur if MP concentrations exceed certain thresholds, which will likely differ dependent on MPs sizes, shapes, composition, and soil properties [64,65,67]. Experimental data within this field is however still sparse and the MP concentrations used in most studies are much higher than concentrations observed in the soil environment, making the actual risk of MPs for soil health still unknown.

4. Future considerations

Nutrients and organic matter in sludge provide an alternative fertilizer source to ensure crop productivity and quality, while enhancing the terrestrial carbon pool improving soil ecosystem functions and services. However, as illustrated in this review, sludge is an important route for agricultural MPs which poses a potential risk to soil health. Future research should therefore consider the following aspects:

Assessing the effect of processes at WWTPs on MP content and properties.

- As part of many sludge treatments, an emulsion polymer is used to flocculate sludge. Emulsion polymers could pose an environmental concern related to MPs if administrated with biosolids on agricultural fields [73].
- Overall lack of studies which include MP concentrations pre- and post-sludge treatment, and thorough effects of sludge treatments on MP properties (section 2.3). Such studies could provide more accurate estimations of overall efficiency among different sludge treatments. And could contribute to better knowledge on appropriate methods to use at WWTPs

Increase understanding of MPs impact on soils as a function of different sludge treatments.

- Investigate how soils react to different sludge treatments. It is important to understand how to minimize MP concentrations without harming soil health, since studies have shown inverse relationship between MP size and impact on soil health (section 3.2).

The influence of management at WWTP and farming systems.

- Size and fate of MPs can be influenced by management practice [1,24,41]. Both at WWTPs and in farming systems. Acknowledgement of this is currently lacking.
- Revisit the sole focus for WWTPs on cleaning the water phase. Future research into reducing the contaminant.

Author statements

Asta Hooge: Conceptualization, Methodology, Investigation, Writing – Original Draft, Visualization. **Henrik Hauggaard-Nielsen:** Conceptualization, Investigation, Writing – Original Draft. **Wiebke M. Henize:** Conceptualization, Investigation, Writing – Original Draft, Visualization. **Gry Lyngsie:** Conceptualization, Investigation, Writing – Original Draft. **Tiffany M. Ramos:** Writing - Review & Editing. **Monica H. Sandgaard:** Investigation, Writing – Original Draft. **Jes Vollertsen:** Writing - Review & Editing. **Kristian Syberg:** Conceptualization, Methodology, Investigation, Writing – Original Draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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