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Look before you leap

Are increased recycling efforts accelerating microplastic pollution?

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Abstract

To fight plastic pollution and reach net-zero ambitions, policy and industry set goals to increase the recycling of plastics and the recycled content in products. While this ideally reduces demand for virgin material, it also increases pressure on recyclers to find suitable endmarkets for the recyclate. This may lead to two effects: a multiplication of recycled content in applications already made of plastic and a substitution of non-plastic materials with cheap, low-quality recyclate. Both areas of application may be sources of microplastic (MP) pollution. Combined with the inherent degradation of recyclate during its lifecycle, but also during recycling, we expect the increase in recycled content will subsequently lead to an increase in MP pollution. We propose a framework to investigate the risk of MP generation through plastic applications throughout their subsequent lifecycle of production, use phase, and end of life. We apply the framework to two prominent examples of recyclate endmarkets, that is, textiles and wood–plastic, and point out where the degradation effects can cause higher release. To conclude, we outline a research agenda to support policymakers in their decision making on specifying targets for recycling and recycled content.

KEYWORDS
circular economy, industrial ecology, microplastic generation, plastics recycling, textile microfibers, wood–plastic composites

1 | INTRODUCTION

Regulatory measures to combat plastic pollution and achieve net-zero targets are discussed and implemented worldwide (Plastic Pollution Treaty, 2022). The EU Circular Economy Action Plan of the Green Deal proposes increased targets for recycling and recycled content, an end to waste exports, and a levy on non-recycled plastic packaging waste (European Commission 2020). The subsequent amendment of the Packaging and Packaging Waste Directive stipulates a recycling rate of 50% (55%) of plastic packaging waste volumes by 2025 (2030) (European Parliament 2018b). Ideally, this will ramp up plastic collection with recyclate replacing virgin material (Kahlert & Bening, 2022). To realize this, recyclers are facing the challenge of finding suitable endmarkets for large quantities of recyclate of varying—and especially low—quality (Klotz et al., 2022). The pressure is further increased by the Circular Plastics Alliance campaign, with pledges from recyclers and recyclate buyers for 2025. While recyclers have committed to supply 10 mt of recycled plastics, converters and other recyclate buyers have submitted a demand of just 6.4 mt (European Commission 2019). This demand gap substantiates the need for recyclers to find markets and applications for their recyclate, especially if of lower quality.

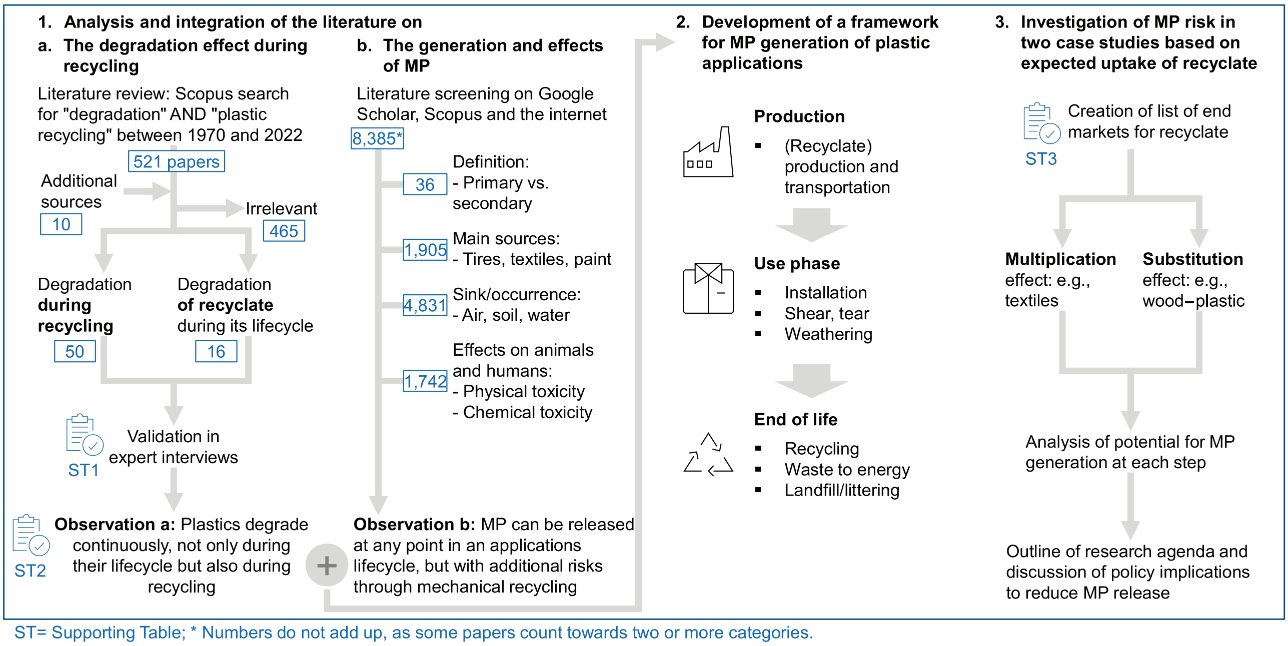


FIGURE 1 Schematic overview of our method.

Although efforts are underway to increase recyclate quality and thus the range of applications, they are ultimately bound to input material quality (CEFLEX, 2020; PreZero, 2022). With design for recycling, separate collection, and improved sorting ramping up slowly, this supply–demand mismatch could solidify. Given the current trajectory, we expect to see two effects: multiplication and substitution. The multiplication effect describes the surge of recycled content in a product made of (virgin) plastic. It occurs when brand owners increase the share of recycled content to meet consumer's sustainability demands, which can be seen with PET bottles or textiles (PepsiCo, 2020; Textile Exchange, 2019). For example, the Recycled Polyester Challenge by Textile Exchange has the goal of reaching 45% (90%) of recycled volume by 2025 (2030)—from 14% today (Textile Exchange, 2019). Alternatively, the substitution effect describes replacing non-plastic materials with recyclate and thus a "plastication" of products. The surplus of cheap, low-quality recyclate leads, for example, to a full (i.e., plastic lumber) or partial (i.e., wood–plastic composite; WPC) substitution effect of wood, as already visible in developing countries (Jubinville et al., 2020; Keskisaari & Kärki, 2018).

These two effects lead to an increase in lower-quality plastic applications. This can be especially problematic regarding the generation of MPs, for two reasons inherent to the prevalent mechanical recycling: (1) potential degradation of polymers during recycling and subsequent usage and (2) complex mix of additives from input material. Degradation can cause plastics to become brittle, making them prone to shed MPs (Al-Salem, 2019; Ragaert et al., 2017). Prevalent additives can further exacerbate the degradation (i.e., metal salts used in oxo-degradable applications) and simultaneously pose a vector for toxication (Wiesinger et al., 2020, 2021). Depending on the recyclates' application, this can lead to accelerated weathering during usage and subsequent release of MPs. We thus hypothesize that the widely requested increase in plastics recycling can have multiplication and substitution effects that can ultimately lead to more MP pollution.

In this paper, we review polymer degradation during mechanical recycling, incorporate knowledge about microplastics (MPs), and introduce a framework to assess MP pollution across a plastic application's lifecycle. We apply this framework to textiles and wood–plastic as potential end-markets of recyclate. Our findings reveal a significant risk of MP release from both applications with increased recyclate usage. Further research in recyclate degradation and MP generation is essential. We establish a research agenda for studying recycling's degradative effects, recyclate weathering, and MP release to aid regulatory decision making on recycling and recycled content targets.

2 | METHOD

Our method is divided into three steps (see Figure 1): (1) literature analysis on (a) degradation effects during mechanical recycling and (b) generation and effects of MPs; (2) framework development for assessing the generation of MPs through plastic applications throughout their lifecycle; and (3) investigation of the risk of MP release in two case studies that are potential candidates for recyclate uptake, that is, textiles and wood–plastic. The individual steps are detailed below.

2.1 | Analysis and integration of the literature on degradation effects during recycling and generation and effects of MPs

For this paper, we integrated two literature streams to investigate the relationship between polymer degradation during mechanical recycling and MP release in subsequent product applications throughout the lifecycle of production, use phase, and end of life. Due to different processing parameters and degradation effects, we only consider mechanical recycling—currently the most prevalent technology.

We followed an interdisciplinary multi-method approach to examine the effects of polymer degradation during mechanical recycling. We started with a broad literature screening to understand relevant keywords, processes, and effects. Building on this, we performed a bibliographic search via Scopus on “plastic recycling” AND “degradation.” This yielded 521 papers, which we screened by title, abstract, and journal, and an additional 10 sources through references, recommendation sections, and further searches. We sorted results into three categories depending on their focus area: (1) degradation during recycling, (2) degradation of recyclate during its lifecycle, and (3) irrelevant papers. We excluded sources primarily discussing bioplastics, special polymers, or tertiary and quaternary recycling technologies (i.e., enzymatic or chemical recycling) (Al-Salem et al., 2009).

In total, we identified 50 papers relevant for degradation during recycling and 16 papers for degradation of recyclate (see Table S2). Subsequently, we performed an in-depth analysis of the papers discussing degradation during recycling, which we summarize in Section 3.1. Additionally, we reviewed the papers focusing on degradation of recyclate for downstream effects as well as various endmarkets to support the selection of the case studies. We discussed and validated our hypothesis in 15 expert interviews with academia and industry (see Table S1 in Supplementary Information).

In parallel, we studied the literature on generation and effects of MPs to understand relevant factors for MP release. We started with a literature screening on Google Scholar, Scopus, and through search engines, yielding 8,385 papers. Additionally, we analyzed key reports regarding main sources of MP relevant to the EU, namely SAPEA (2019), Eunomia (2016), and Boucher and Friot (2017). In our analysis, we distinguished between papers focusing on the definition (36 papers), generation (1905), occurrences, and sinks (4831) of MPs as well as their toxicity, uptake by, and effects on animals and humans (1742). The results of this analysis are summarized in Section 3.1 and serve as the basis for the framework development.

2.2 | Development of a framework for MP generation in plastic applications

Our results from the first two steps show that (1) plastics continuously degrade not only during their lifecycle but also recycling; and (2) MPs can be released at any point throughout an applications' lifecycle, but with additional risks for release and toxic leaching through mechanical recycling. However, existing studies on MP generation focus either on specific use cases (e.g., release during textile washing and tire wear during driving) or total estimated generation in certain countries or regions across sources. As of today, no systematic method has been established to investigate the risk of MP generation along the lifecycle for a specific application. Thus, we propose a framework to analyze this from production over usage to different end-of-life scenarios such as recycling, (unmanaged) landfill, or incineration.

2.3 | Investigating the risk of MP release in two case studies based on expected uptake of recyclate

We selected two key recyclate endmarkets for applying our framework. Utilizing expert interviews, industry reports, and research on recyclate trading platforms, we compiled a list of existing and potential EU endmarkets for specific polymers (high-density polyethylene [HDPE], low-density polyethylene [LDPE], PET, and PP), considering the increased availability of recyclate (see Table S3 in SI). We selected the EU as our focus area due to its extensive regulatory framework and subsequent recycling and recycled content targets. Driven by high plastic consumption, it has built up the most advanced collection and recycling infrastructure. Additionally, data availability and expert networks facilitated a thorough evaluation of recyclate endmarkets. To identify two endmarkets, we categorized potential options by multiplication and substitution effects. Leveraging literature and expert insights, we selected a prominent example from each effect as case studies: textiles and wood–plastic. Textiles experience a multiplication effect due to growing consumer demand for sustainable materials (Textile Exchange, 2019), while wood–plastic substitutes organic wood with cost efficiency, flexibility, and reduced maintenance (Gardner et al., 2015; Jubinville et al., 2020).

3 | RESULTS

3.1 | Analysis and integration of literature on degradation during recycling and generation and effects of MPs

Our literature analysis showed that plastics also degrade during mechanical recycling—and recyclate constitutes additional risks for releasing MPs and toxic leaching.

3.1.1 | Plastic degradation during recycling

In general, degradation mechanisms for polymers can be differentiated based on the causing factor: bio-, photo-, thermo-oxidative, thermal, and hydrolytic degradation (Andrady, 2011). During mechanical recycling, polymers go through several steps of processing, causing heat and mechanical shear (Ragaert et al., 2017). This combination is called thermo-mechanical degradation, which mostly happens in the melt processing (Beyler & Hirschler, 2002). The degradation process can result in chain scission—for example, for PP (González-González et al., 1998; Jubinville et al., 2021) or PET (Bascucci et al., 2022; La Mantia & Vinci, 1994)—or chain branching—for example, for HDPE (Jubinville et al., 2021; Pinheiro et al., 2004). This leads to a molecular weight change, which can have a strong influence on rheological and mechanical behaviors of polymers, but also on their thermal (e.g., melting point) and physical (e.g., color) properties (Al-Salem, 2019; Ragaert et al., 2017; Schyns & Shaver, 2020). Depending on a polymer's application and lifetime, these degradation effects are added to existing degradation from the use phase (i.e., weathering and aging) (La Mantia, 1996; Vilaplana & Karlsson, 2008). Additionally, even small amounts of other polymers can further change material properties and reduce both recyclability and recyclate quality (Eriksen et al., 2018; Paul et al., 1972). This also applies to the additive mix (Chen et al., 2021; Horodytska et al., 2020) such as plasticizers, antioxidants, and flame retardants (Bascucci et al., 2022; Hahladakis et al., 2018), which is used to achieve required properties. While additional additives such as heat and UV stabilizers are added to the recyclate to reverse this degradation, they can dissolve and/or leach from polymers over time (Klein et al., 2021; Ulutan, 2003).

Moreover, processing aids and non-intentionally added substances can be present in plastics (Geueke, 2018; Horodytska et al., 2020). A recent study identified over 10,000 relevant substances, 2400 of which were of potential concern regarding persistence, bioaccumulation, or toxicity (Wiesinger et al., 2021). One particularly concerning category is pro-oxidants (Babetto et al., 2020; Samsudin et al., 2013). While their targeted usage for oxo-degradable plastics is not widespread, their broadness and complexity pose a threat that they are used in conventional plastics for functionalities other than being pro-oxidant (Wiesinger et al., 2021). Not only can those chemicals impair recycling processes, safety, and quality, but also be released during the plastic lifecycle, resulting in human and environmental exposure (Day et al., 1995; Leslie et al., 2016; Turner, 2018).

To conclude, plastics degrade continuously through thermo-mechanical processes, environmental exposure, and contaminated feedstocks, leading to reduced mechanical properties, accelerated breakdown, and release of toxic substances.

3.1.2 | Generation and effects of MPs

Parallel to Section 3.1.1, we screened the literature on generation and effects of MPs to understand the risk of MP release from degraded recyclate.

MPs were found in both fresh water (Eerkes-Medrano et al., 2015) and oceans (Boucher & Friot, 2017; Eriksen et al., 2014), in soil (Habib et al., 1998), and the atmosphere (Dris et al., 2016)—from the deep sea (van Cauwenberghe et al., 2013) to polar regions (Obbard et al., 2014). First findings date back to 50 years (Carpenter & Smith, 1972), but research on MPs' impact and distribution only commenced in 2004 (Thompson et al., 2004). While MPs are defined as particles of synthetic polymers between 1 µm and 5 mm (Arthur et al., 2009; Lambert & Wagner, 2016), they come in different sizes, shapes, and dimensions (Kooi & Koelmans, 2019). MPs can be produced intentionally (primary) or form by fragmentation during use or degradation and weathering in the environment (secondary) (GESAMP, 2015; Hartmann et al., 2019). Tires, paints, textiles, and personal care products have been identified as main MP sources (Hann et al., 2018; Lau et al., 2020; Paruta et al., 2022), but can be generated anytime, whether through opening plastic packaging (Sobhani et al., 2020) or the breakdown of macroplastic litter (Napper & Thompson, 2019).

MPs may act as vectors for harmful additives and contaminants from production and usage (Teuten et al., 2009). Furthermore, due to their hydrophobic behavior, MPs can absorb, transport, and leach toxic chemicals (Bakir et al., 2014; Teuten et al., 2007). Reported chemicals include heavy metals (e.g., iron and manganese) and persistent organic pollutants (e.g., polyaromatic hydrocarbons and organochlorine pesticides) (Capolupo et al., 2020; Verla et al., 2019). Recent studies suggest that MPs make organic pollutants an order of magnitude more toxic (Rubin & Zucker, 2022) and recycled MPs leach more organic components than virgin ones due to unintentional accumulation of chemicals (Fatunsin et al., 2020; Li et al., 2021).

Depending on their size and point of release, MPs can be ingested or inhaled by humans and animals, leading to a number of adverse effects (see Material S1) (Prata et al., 2020; Wright et al., 2013).

In conclusion, MPs can be released anywhere in an applications' lifecycle, with MPs from recyclate exhibiting increased leaching and thus potentially more severe effects on humans and animals. Given the limited research, it is important to further investigate this issue.

3.2 | Framework to assess the generation of MPs through plastic applications

We have developed a framework to analyze processes in production, usage, and end-of-life scenarios that incur a high risk of releasing MPs. The framework includes both direct (and measurable) release of MPs and indirect effects—such as degradation during production processes—driving

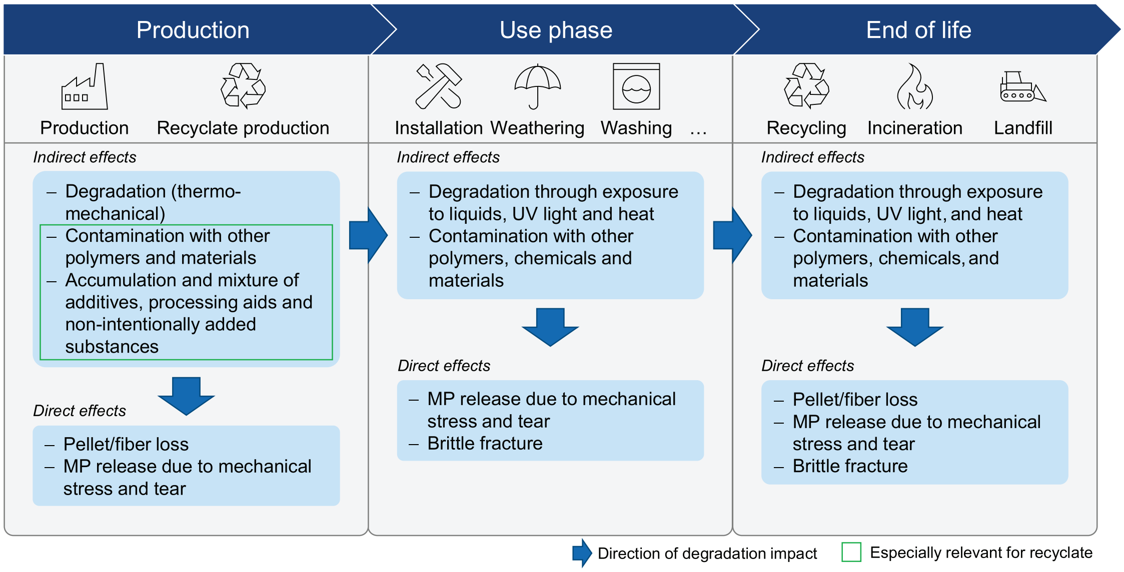


FIGURE 2 Framework to analyze generation of microplastics throughout the plastics lifecycle.

the MP release further down the lifecycle of products. Arrows indicate degradation's influence on MP release, for example, thermo-mechanical degradation in production affects the risk of MP release in both production processes themselves and subsequent use phases. This allowed us to perform a holistic analysis of the MP potential of certain plastic applications over its lifecycle (see Figure S1 in Supplementary Information for an overall framework).

As the paper centers on MPs generated by greater recyclate usage, we extended the framework to incorporate indirect effects during recyclate production and processing (Figure 2—green box).

3.3 | Investigating the risk of MP release in two case studies

By applying our framework, we investigated the risk for additional MP release for two relevant endmarkets susceptible to a multiplication or substitution effect: textiles and wood–plastic.

3.3.1 | Analysis of additional MP release in textiles (multiplication effect)

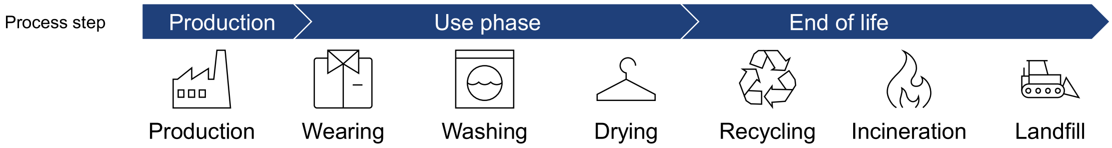
Textiles are among the main endmarkets for recyclate—especially for recycled polyethylene terephthalate (rPET) (Eunomia, 2020). In 2020, the sector took in over 8.4 m tons of recyclate, driving the share of rPET fibers to 14.7%—from 13.7% in 2019 (Textile Exchange, 2021). This trend is likely to accelerate, with >140 apparel companies adopting the 2025 Recycled Polyester Challenge created by Textile Exchange, pledging to drive rPET usage up to 45% (90%) by 2025 (2030) (Textile Exchange, 2021). Simultaneously, global fiber production is expected to grow by 34% between 2020 and 2030, with an increasing share of synthetic fibers (Textile Exchange, 2021). In total, this would result in an intake of 30.6 mt (75.6 mt) tons of recyclate by 2025 (2030) (see Material S2).

To understand the heightened MP generation risk with greater recyclate usage, we examined MP sources in the textile lifecycle (production, use, and end of life), identifying degradation-related shedding. We concentrated on garments, responsible for 85% of global fiber production and a significant European MP source (Hann et al., 2018; Quantis, 2018). Figure 3 summarizes the main findings of the case study, including relevant processes, most important parameters for MP release, and state of research.

Production

The textile production chain includes the sourcing of raw materials, processing into fibers, spinning of yarn, manufacture of fabrics, and production of garments (Cai et al., 2020; Sandin & Peters, 2018). For recyclate, the process starts with converting PET flakes, pellets, or chips into fibers by melt extrusion and spinning (Palacios-Mateo et al., 2021; Shen et al., 2010).

In textile production, there are two different types of MP losses: (1) pellets and (2) microfibers (MFs).



	Production	Wearing	Washing	Drying	Recycling	Incineration	Landfill
Important parameters	(Recyclate) production process and parameters, open or closed layout	Production parameters, performed activity	Production parameters, washing cycle and load, detergent usage and temperature	Air or electric, drying cycle, filter and cleaning process	Recycling technology and parameters, open or closed layout	Type of furnace, temperature, origin and separation of waste	Landfill setup, waste composition
State of research	Little research available	Little research available	Highly researched	Some research available	Little research available	No research available	No research available

FIGURE 3 Evaluation of microplastic sources and their investigation throughout the textile lifecycle.

Loss of pellets was estimated as second-largest source of MPs in Europe (Hann et al., 2018), with an average rate of 0.04%–1% (see Material S3). For recycling plants, wastewater has been identified as major carrier of MP pollution if the effluent is not filtered (Suzuki et al., 2022). Simultaneously, the total loss can be expected to increase in proportion to the amount recycled.

The release of MFs in subsequent garment production has not been analyzed in detail yet, as most studies focus on washing during usage. However, textiles are also washed during production, resulting in MF release through wastewater effluent (Chan et al., 2021).

The production process lays the foundation for subsequent susceptibility to shedding. For example, the material blend (Napper & Thompson, 2016), yarn length (De Falco et al., 2018, 2020) and twist (Lawrence, 2003; Özkan & Gündoğdu, 2021), as well as knitting technique (Carney Almroth et al., 2018), and whether mechanical or chemical finishing treatments are applied (OECD, 2020) all influence shedding. Mechanical processes, such as fleece brushing or fabric aging further weaken fibers and lead to a higher MF release (Roos et al., 2017) (see Table S4 for full list of parameters).

To summarize, research on production processes is limited, but MF release can increase with shorter and more loosely woven fibers as well as through mechanical stress and tear. Shorter fibers in recycled textiles have indeed been found to increase shedding by up to 2.3 times in two studies (Özkan & Gündoğdu, 2021; Zwart & Valk, 2019) (see Material S4). Increased MF release through a breakdown of recycled fibers' mechanical structure is thus highly likely (Rengel, 2017).

Use phase

During usage, primary causes of MF loss are wearing, washing, and drying (Jönsson et al., 2018).

MFs are released during wear through actions like movement and abrasion (Cai et al., 2021). This release is on par with washing, and up to 65% of these released MFs enter the ambient air (De Falco et al., 2020; OECD, 2020). Sitting or moving on furniture can increase fiber release significantly. The release during wear depends on production factors and activities performed. Recycled polyester textiles with shorter fibers likely contribute to higher MF release (Cai et al., 2021).

Numerous studies have examined MF release during machine washing, considering factors such as garment production, machine type, detergent, and the use of filters or other technologies (Hartline et al., 2016; Jönsson et al., 2018; McIlwraith et al., 2019; Pirc et al., 2016) (see Table S4 for a full list of parameters). MFs can enter the environment through wastewater, depending on treatment methods (see Material S5).

Overall, washing is the most researched process for textiles, given its high relevance for MF release. The expected increase through recyclate usage has been investigated, but a standardization of methods would help to improve the comparability of results.

Textiles can be dried by air or electric dryers. While air drying is expected to release MFs (Dris et al., 2017), no studies have quantified this. Electric dryers can emit potentially 3.5 times more MF than washing (Pirc et al., 2016). While inbuilt filters capture most fibers, their release can still occur during cleaning (O'Brien et al., 2020). The release varies with dryer type, garment parameters, age, vent installation, and lint-trap characteristics (Kapp & Miller, 2020). No studies have been conducted with recycled textiles, which also pose a risk of MF release due to shortened fibers (Rengel, 2017).

End of life

At the end of usage, textiles are usually collected with household waste or through charitable organizations (e.g., Salvation Army and Red Cross) with the intent to recycle or resell them. Additionally, a few municipalities already practice separate collection, which will be mandatory across the EU by 2025 (European Parliament 2018a). Textiles are then recycled, sent to landfill, or incinerated (see Material S6).

For recycling, there are three different technologies of both pre- and post-consumer textile waste: mechanical, chemical, and thermal recycling (Ellen MacArthur Foundation, 2017; Sandin & Peters, 2018). Mechanical recycling shreds textiles, resulting in shorter fibers and lower material quality, making them more prone to MF release (Brouw, 2019; Payne, 2015). Chemical recycling depolymerizes and repolymerizes materials for virgin-like quality (Regel, 2017), whereas in thermal recycling, thermoplastic fibers such as polyester are melt-spun through the same process as

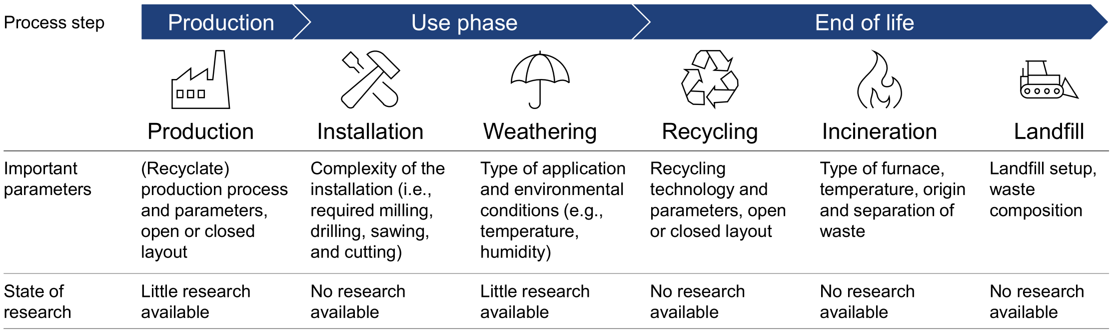


FIGURE 4 Evaluation of microplastic sources and their investigation throughout the lifecycle of wood–plastic composite.

virgin fibers (Heikkilä et al., 2019). While both technologies could significantly reduce polymer degradation and subsequent MF generation, they are currently not available at commercial scale (Ellen MacArthur Foundation, 2017; Heikkilä et al., 2019). Most textiles are thus recycled mechanically into lower-value applications like insulation, stuffing material, and wiping cloths (Nikolina, 2019; Schmidt et al., 2016). Depending on the tear, stress, and environmental effects, an increase in MF release is expected from recycled fibers.

Overall, MF release during recycling is sparsely researched but has a high risk of increasing with an expansion of mechanical recycling capacities and continual degradation of materials, especially across multiple recycling cycles (Suzuki et al., 2022).

Although incineration has been used to eliminate plastic waste (Geyer et al., 2017), recent research found that bottom ash residue still contains significant amounts of MP, including polyester fibers (Yang et al., 2021). The quantity varies depending on various parameters (see Material S7), however neither the allocation to individual textiles nor the difference in MP release between virgin and recycled material has been investigated so far. However, the shorter length of recycled fibers could lead to improved combustion and thus lower shedding.

Landfilling is the primary disposal method for EU textiles. Polymers in landfills can degrade through several ways, leading to the release of MF into the environment through air or effluent (Rillig, 2012; Sun et al., 2021), potentially contaminating groundwater (see Material S8). While the average polyester product can persist for more than 200 years (Goldsworthy, 2013), the degradation of recycled textiles in landfills has not been investigated in detail. However, they could degrade much more quickly due to their shorter fiber length, increasing MF release (Rengel, 2017).

In summary, washing and drying are primary MP release processes, with production and wearing following closely. While recyclate use has been unexplored outside washing, an increase can be anticipated across usage, production, and recycling. Landfill may see a slight increase with recyclate adoption, while incineration could potentially reduce MP release. Overall, without preventive measures, recyclate use could significantly boost release. To quantify these releases, further research is essential.

3.3.2 | Analysis of additional MP release in wood–plastic (substitution effect)

Wood can be replaced partially ("WPC") or fully (plastic lumber, "PL") by virgin or recycled plastics. This substitution reduces both cost and maintenance but contributes to the omnipresence of plastic waste. The European WPC market is estimated at 450k tons in 2021, with 8% annual growth until 2027 (Mordor Intelligence, 2021). For PL, only a forecast of $8.24bn global revenue by 2025 is available publicly (IndustryARC, 2020). While PL was sought after at the beginning of the 21st century, most applications rely on WPC due to its improved mechanical properties; hence, we will focus on WPC.

The majority of WPC could already come from recyclate, as its applications pose an integral part of the largest endmarkets of recyclate, for example, building and construction (46% of recyclate), automotive (3%), and others (11%) (PlasticsEurope, 2020). Due to the expected rise in recycling and subsequent availability of recyclate in different qualities, a significant increase in WPC production is expected (Keskisaari & Kärki, 2018).

Similar to the textile case, we analyzed the processes throughout the lifecycle of wood–plastic that could be prone to releasing MPs. However, to date, no studies have been conducted to determine the MP emissions of either WPC or PL. The following section thus refers primarily to the indirect effects described in the framework and qualitatively discusses the potential for an increase in emissions through recyclate usage. Figure 4 summarizes process steps, most important parameters for MP release, and the state of research of this case study.

Production

The production of WPC requires melting points below the degradation temperature of wood (i.e., around 220°C), as it is blended with wood fibers or flour in the extrusion process to improve mechanical properties (Gardner et al., 2015). Common polymers are HDPE, LDPE, PP, polyvinyl chloride (PVC), and occasionally PET (Chiou et al., 2022; Jubinville et al., 2020).

Compared to the textile case study, there is only one source of MP loss during WPC production, that is., the loss of pellets before extrusion of ~0.1% for both virgin and recycled production (Essel et al., 2015). While there might be minor losses through abrasion during finishing, packaging, and transportation of products, we expect these to be negligible in comparison to other sources.

Here, too, production processes have an indirect effect on MP release during usage. In particular, polymer composition (Chiou et al., 2022), wood component ratio (Matuana & Kamdem, 2002; Seldén et al., 2004; Stark & Matuana, 2006), load of additives and compatibilizers (Bengtsson et al., 2007; Panthapulakkal & Sain, 2006), and manufacturing method (Stark & Matuana, 2006) can influence WPCs' mechanical properties and degradation.

For recycled material, potential contamination with other polymers and materials as well as accumulation and mixture of additives, processing aids, and non-intentionally added substances further contribute to degradation (Jubinville et al., 2020; Kazemi Najafi, 2013). This can lead to lower strength and stiffness (Youngquist et al., 1994), reduced flexural modulus (Kamdem et al., 2004), and ultimately surface cracking and embrittlement, which increases the likelihood of MP shedding (Basalp et al., 2020; Gustavo Barbosa et al., 2017; Turku et al., 2018). While some materials (e.g., HDPE) and processes (e.g., extrusion) are preferable to others, a definite answer on optimal parameter combination is not yet possible at the current stage of research (Stark & Matuana, 2004).

Use phase

The use phase can be split into the installation of the WPC and weathering during usage. During installation, the material can be milled, drilled, sawed, and cut, which will create MPs in the form of sawdust. Since many applications are installed outdoors (e.g., decking, railing, and fencing), MPs are lost directly to the environment (Gardner et al., 2015). Here, too, there are no scientific studies, which is why no quantitative assessment is possible.

During the use phase, the applications are exposed to the environment and thus prone to a variety of previously discussed weathering and degradation mechanisms. Many studies have been conducted on decay through fungi, rotting, humidity, water sorption, or discoloration (Chiou et al., 2022; Gardner et al., 2015; Homkhiew et al., 2014). Wood contents are particularly prone to degradation, with higher resistance in coextruded composites (Wei et al., 2022). However, subsequent release of MPs has not yet been researched.

With the addition of recyclate, a higher level of degradation has been investigated (Chan et al., 2019; Turku et al., 2018). Kazemi-Najafi and Englund (2013) thus proposed a maximum of 10% of recycled material for WPC from HDPE and pine-wood flour to reduce cross-linking and achieve acceptable processability and mechanical properties. While additional shedding through increased degradation is highly likely, there are no studies to date to confirm this.

End of life

The potential end-of-life treatment of WPC includes recycling, landfilling, littering, and incineration. Due to its long service life (30–40 years) (IBU, 2015a, 2015b) and the lack of separate collection, a breakdown of treatments in Europe is unknown. However, a majority of WPC presumably ends up in incineration because recycling is technically challenging and not economically feasible (Sommerhuber et al., 2015, 2017).

MP shedding from wood–plastic during incineration has not been extensively researched but can be assumed in comparison to other materials. While wood flakes are easily combustible, polymers require high temperatures for complete combustion (Burge & Tipper, 1969). The presence of flame retardants in WPC may make combustion more difficult and lead to a higher abundance of MPs in bottom ash (García et al., 2009; Yang et al., 2021). It is unknown whether recyclate affects MP release.

Although recycling and landfilling are neither prominent nor studied, increased embrittlement from degradation during production and usage could increase MP release.

Overall, research on MP generation through WPC is very limited, but current studies suggest risks of both degradation and release into the environment, especially with recyclate. Additional MP release could happen during installation, recycling, and landfilling, but more research is needed to substantiate and quantify results.

4 | DISCUSSION

In addressing plastic pollution, recycling receives significant attention from both regulators and industry investors. However, low recyclate quality presents challenges for finding suitable endmarkets. With impending regulations to boost recyclate production, we anticipate increased application variety (e.g., wood–plastic) and recycled material usage (e.g., textiles), posing a significant risk of MP release in both cases. For textiles, without preventive measures, we foresee a notable MP increase due to shedding. In the case of wood–plastic, particle release across the application's lifecycle is expected to rise.

This paper serves as a call to action for interdisciplinary research, spanning environmental toxicology and chemical engineering, with a focus on degradation processes during the transition from the 1st to the 2nd lifecycle and subsequent stages. We highlight current literature limitations (Section 4.1) to identify areas requiring further research, outlining a research agenda that emphasizes policy dimensions. Specifically, we discuss the interaction between recycling and recycled content targets in creating sustainable endmarkets and its implications for policymakers (Section 4.2).

4.1 | Extend research on the generation of microplastic through the uptake of recyclate

We identify three primary research areas that require further development: first, in plastic recycling, encompassing the examination of degradation's influence on recyclate, the generation and consequences of secondary MP; second, the enhancement of recycling processes; and third, the deployment of preventive measures to tackle challenges presented by degraded recyclate across applications, with a specific focus on textiles.

First, degradation through recycling and addition of additives to prevent degradation has been researched since plastic recycling was first taken up (La Mantia & Vinci, 1994). However, the effect of degradation on subsequent use phases of recyclate has not been investigated in detail. In addition, most studies use virgin feedstocks to test degradation, thus neglecting degradation from previous use phase(s). Field testing and more realistic study setups are needed to better understand the processing of degraded polymers including contaminant and additive mixes—research that could shed light on possible obstacles in re-use systems. More precisely, a better understanding of generation and long-term effects of secondary MPs—for example, for particle load and toxicity—is required. Research on generation is currently focused on primary MPs and/or specific parts of production/use phases. Our proposed framework to assess MP generation can be integrated with existing work on exposure pathways (Peng et al., 2021) and environmental risk assessment (Gouin et al., 2019) to gain a better understanding of MP generation and effects. However, many studies only use microbeads, including when comparing virgin and recyclate particles—which can distort results (Rubin et al., 2021). In addition, researchers often work with artificially high MP concentrations to achieve effects, rendering it impossible to draw conclusions about actual impacts of real-world concentrations in the environment (Burns & Boxall, 2018). In addition, measurements of MP releases are often performed with a lower limit, possibly overlooking nanoparticles, and thus underestimating overall particle loads.

Second, more research is needed on improved recycling processes and parameters to reduce degradation. For example, tertiary recycling (i.e., chemical/enzymatic) can enable the breakdown of plastic applications into monomers, but is currently not available at scale (Singh et al., 2017; Solis & Silveira, 2020).

Third, more research is needed on preventative measures and their potential. For textiles in particular, many mitigation measures are already under consideration, from design and manufacturing to the addition of external/built-in filters for washing machines and wastewater treatment plants (McIlwraith et al., 2019; OECD, 2020; Talvitie et al., 2017). However, increased usage of degraded recyclate with unknown and varying mixtures of additives poses new challenges that must be carefully monitored—ideally before new markets are developed.

4.2 | Consider the risk for MP generation and toxicity in the design of (regulatory) interventions for endmarkets

The following section has two parts: (1) policies nurturing the uptake of recyclate and (2) (lack of) policies that would focus on MP generation as a potential effect of those policies described in (1).

Although the waste pyramid positions recycling as third-worst solution after disposal and energy recovery, industry and policy currently prioritize it as the greatest potential to solve the plastics crisis. This is reflected in numerous new and existing policies, most prominently in the European Strategy for Plastics in a Circular Economy (European Commission 2018). Policymakers can steer the recyclate flow through recycled content targets, as has been done with PET bottles, mandating 25% by 2025 (European Parliament 2019). Additional targets for plastic packaging are expected soon (European Commission, 2022), and have already found broad support from industry (Vasile, 2021). Only recently, the discussion on how to scale-up certain recycling technologies—namely, chemical recycling—has taken off. Until then, policies had mostly been technology agnostic. Simultaneously, industry has made substantial pledges to increase recycled material in its products (Kahlert & Bening, 2022). When recyclate has a reasonable value, which would be an intermediate goal of these regulatory interventions, investment in collection and recycling increases, reducing subsequent pollution and macro-littering. Of course, recycling has its benefits, given that plastics might otherwise disintegrate in the environment, end up in landfill, or be lost through incineration. This directly translates into less secondary MP through fragmentation, which is potentially the largest source of MP generation in the long term (Mitrano & Wohlleben, 2020).

In sum, there is a clear move toward recycled material, although it is still open whether this will be the case for all kinds of products or only those where virgin plastic can be replaced—and, if so, which applications will be targeted primarily, if not all. Currently, the mere increase of recycled content is oftentimes the main objective in regulation and innovation activities. However, we see a potential dilemma if this is pursued regardless of recyclate quality, substituted material, and the fact that the application may have adverse effects on the overall goal of reducing negative externalities on the environment through MP generation.

Therefore, we encourage policymakers to carefully integrate the risk of MP generation from different endmarkets in their consideration regarding recycling. Clearly, economic reasoning can justify a largely application-agnostic policy on recycled content, but our research strongly suggests that this may lead to adverse effects. The selection of endmarkets for recyclate and respective regulatory interventions must consider the risk of MP release. One way to do this would be the mandatory inclusion of LCAs when bringing new products to market. First suggestions have been made on how to include MP release in LCAs (Henry et al., 2019; Kawecki & Nowack, 2019).

To better understand degradation and toxicity, we need more data on the composition of plastics and plastic waste. First steps in this direction have been taken by setting requirements for product design, for example, the Single-Use Plastics Directive by the European Parliament (2019), and reducing product complexity, as considered in the EU Circular Economy Action Plan (European Commission 2020). The subsequent tracking of plastics, their additives, and recyclate could ensure safe handling and improves allocation to suitable endmarkets (PolyREC, 2022).

The issues raised in this paper have entered the political debate indirectly, most prominently in the current zero draft for a legally binding UN Treaty on Plastic Pollution (UNEP, 2023). Intentional MP release is specifically tackled, and MP in general (but without alluding to secondary MP) is covered in the section on "emissions and releases of plastics throughout its life cycle." To what extent the concerns raised in this paper will be addressed in the treaty depends on the still to be written definition of "problematic and avoidable plastic products" (Note 13) and "safe and environmentally sound post-consumer recycled plastic" (Note 27). The additional research in areas as suggested in this paper would be directly beneficial for this important policymaking process. Ultimately, collection, sorting, or even recycling can only be a means to a greater end (Blum et al., 2020). That is why, when establishing new markets, it is so important to carefully consider *all* the pros and cons—and look before you leap.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available in article supporting information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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