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Short communication

# Macroplastic fragmentation in rivers

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ABSTRACT

The process of macroplastic (>0.5 cm) fragmentation results in the production of smaller plastic particles, which threaten biota and human health and are difficult to remove from the environment. The global coverage and long retention times of macroplastic waste in fluvial systems (ranging from years to centuries) create long-lasting and widespread potential for its fragmentation and the production of secondary micro- and nanoplastics. However, the pathways and rates of this process are mostly unknown and existing experimental data not fully informative, which constitutes a fundamental knowledge gap in our understanding of macroplastic fate in rivers and the transfer of produced microparticles throughout the environment. Here we present a conceptual framework which identifies two types of riverine macroplastic fragmentation controls: intrinsic (resulting from plastic item properties) and extrinsic (resulting from river characteristics and climate). First, based on the existing literature, we identify the intrinsic properties of macroplastic items that make them particularly prone to fragmentation (e.g., film shape, low polymer resistance, previous weathering). Second, we formulate a conceptual model showing how extrinsic controls can modulate the intensity of macroplastic fragmentation in perennial and intermittent rivers. Using this model, we hypothesize that the inundated parts of perennial river channels—as specific zones exposed to the constant transfer of water and sediments—provide particular conditions that accelerate the physical fragmentation of macroplastics resulting from their mechanical interactions with water, sediments, and riverbeds. The unvegetated areas in the non-inundated parts of perennial river channels provide conditions for biochemical fragmentation via photo-oxidation. In intermittent rivers, the whole channel zone is hypothesized to favor both the physical and biochemical fragmentation of macroplastics, with the dominance of the mechanical type during the periods with water flow. Our conceptualization aims to support future experimental and modelling works quantifying *plastic footprint* of different macroplastic waste in different types of rivers.

## 1. Introduction

Rivers are practically unexplored as macroplastic (plastic particles larger than > 0.5 cm) fragmentation environments, and field-based information on its control and rates here is mostly unknown (Delorme et al., 2021; Williams and Simmons, 1996). However, in most climates, river channels are characterized by a continuous flow of water and sediments and exposure to sunlight, which can favor the fragmentation of macroplastic waste through both physical and mechanical forces. Moreover, recent works have indicated that rivers are polluted with macroplastic globally, and the timescales of its retention in fluvial system can range from years to centuries (Liro et al., 2020; van Emmerik et al., 2022). This long-lasting presence and widespread occurrence of macroplastics in rivers pose risks of the production and dispersal of secondary micro- and nanoplastics in and beyond rivers.

Existing works have demonstrated that macroplastic can be fragmented into smaller micro- (<1–5 mm) and nanoplastic particles (<0.1–1 μm) through biochemical and physical forces (Andrady, 2015; Dimassi et al., 2022; Gewert et al., 2015; Hurley et al., 2020; Zhang et al., 2021) (Fig. 1). The produced microparticles (called secondary micro- and nano-plastics) are difficult to track and remove from the environment (Napper and Thompson, 2019; van Wijnen et al., 2019) and are known to pose numerous risks for biota and human health (Leslie et al., 2022). The process of macroplastic fragmentation, defined as the breaking of a macroplastic object into smaller particles, in the environment is very poorly understood, and up to now, it has mostly

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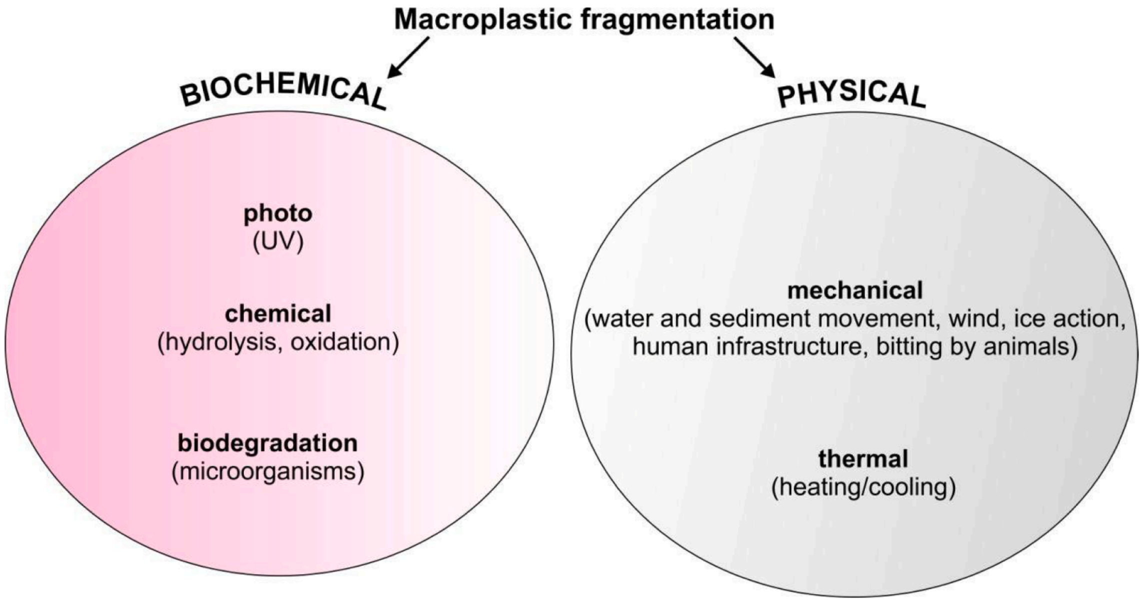


**Fig. 1.** Outline of the types of forces which can result in macroplastic fragmentation. The proposed division into biochemical and physical degradation and fragmentation processes was developed based on previous works (Andrady, 2015; Dimassi et al., 2022; Gewert et al., 2015; Zhang et al., 2021) (for details, see Section 2).

been studied in oceans (Andrady 2015; Andrady et al., 2022; Dimassi et al., 2022; Zhang et al., 2021) or by laboratory experiments (Boersma et al., 2023; Chubarenko et al., 2020; Gerritse et al., 2020; Kalogerakis et al., 2017; Lambert and Wagner, 2016). The macroplastic fragmentation rate is quantified by (i) the loss of weight of the macroplastic object (mass loss/time) (e.g., Maga et al., 2022), (ii) changes in its surface characteristics (e.g., surface roughness change (Reineccius et al., 2023)) or specific surface degradation rate (e.g., SSDR in Chamas et al., 2020), or (iii) the number or mass of microparticles produced (e.g., Lambert and Wagner, 2016).

Among the physical forces able to fragment macroplastic, mechanical force, such as wave action on a beach, is known to provide an opportunity for the collision and abrasion of macroplastic, resulting in its breakdown (Corcoran et al., 2009). Recent experiments showed that macroplastic fragmentation induced by mechanical forces (or the interaction of mechanical and biochemical forces) can proceed a few orders of magnitude faster than that resulting from solely biochemical forces (Sun et al., 2022). Moreover, microparticles produced through the interaction of biochemical and mechanical fragmentation are smaller (nanometer scale) than those produced through solely biochemical fragmentation (see Sun et al., 2022). Mechanical fragmentation accelerates biochemical fragmentation, by increased surface area of macroplastic available for biochemical procesess (Chamas et al., 2020) and surface textural changes, which initiate them (Cooper and Corcoran, 2010; Corcoran et al., 2009; Song et al., 2017; Zbyszewski and Corcoran, 2011) (Fig. 2). This relationship also indicates the importance of mechanical fragmentation, which can be seen not only as a product of macroplastic degradation but also as an environment-dependent process (Andrady, 2015; Hurley et al., 2020) which, itself, can accelerate the rate of macroplastic fragmentation (Sun et al., 2022) (Fig. 2) and thus control the future presence of macroplastics in the environment.

Some previous works have pointed out that macroplastic can be fragmented in rivers (Williams and Simmons, 1996; Delorme et al., 2021), but there were no works which set conceptual frame for more detailed study of this process. To set a starting point for the future exploration of this knowledge gap, here, we developed a conceptual frame for the study of riverine macroplastic fragmentation. First, we divided controls of riverine macroplastic fragmentation into intrinsic (resulting from plastic item properties) (Section 2.1; Table 1; Fig. 3) and extrinsic (resulting from river characteristics and climate) factors (Section 2.2; Fig. 4). Then, we conceptualize and hypothetize (Table 2) how extrinsic controls can modulate the fragmentation of macroplastics transported and stored in the inundated and non-inundated parts of the river channel. Our conceptualization can help planning of future experimental works aimed at the direct quantification of macroplastic fragmentation rates in rivers.

## 2. Conceptualizing riverine macroplastic fragmentation

In this paper we defined process of *macroplastic fragmentation* as breaking of macroplastic object into smaller particles. This process is closely related to more general *macroplastic degradation* process, defined in previous studies as change in physical and chemical properties of macroplastic object, resulting from influence of UV radiation (*photodegradation*), oxygen (*oxidation*), water (*hydrolysis*), high temperature (*thermal degradation*), microorganism (*biodegradation*) or mechanical stress (*mechanical degradation*) (Andrady, 2015; Zhang et al., 2021). The process of macroplastic fragmentation can be seen as direct effect of macroplastic degradation–leading to the loss of physical properties of macroplastic object, ultimately resulting in its disaggregation. It can be also treated as a precursor and accelerator of degradation process because increased surface area of fragmented macroplastic make its area available for further degradation process larger (Andrady et al., 2015; Zhang et al., 2021). In the previous works terms degradation and fragmentation have been used interchangeably and called also an *abrasion*, *breakdown*, *weathering*, *ageing*, *erosion*, *attrition*, ablation (see e.g., Zhang et al., 2021 and literature cited therein) (Fig. 2). We categorized the types of macroplastic fragmentation, in relation to their main control factors, into *biochemical fragmentation* and *physical fragmentation,* similarly as was previously used for plastic degradation processes (Andrady, 2015; Dimassi et al., 2022; Gewert et al., 2015; Zhang et al., 2021). Biochemical fragmentation is defined as the breaking of macroplastic objects into smaller particles as a resulting of photodegradation (via UV irradiance), oxidation, hydrolysis, and biodegradation by microorganisms. Physical fragmentation is defined as the breaking of macroplastic objects into smaller particles as a result of mechanical and thermal factors. In the riverine environment, mechanical fragmentation describes the breaking of macroplastic objects as a result of interactions with the riverbed, water, and sediments (mineral, organic, synthetic), as well as plants (e.g., root action), ice (collision, freezing/thawing),

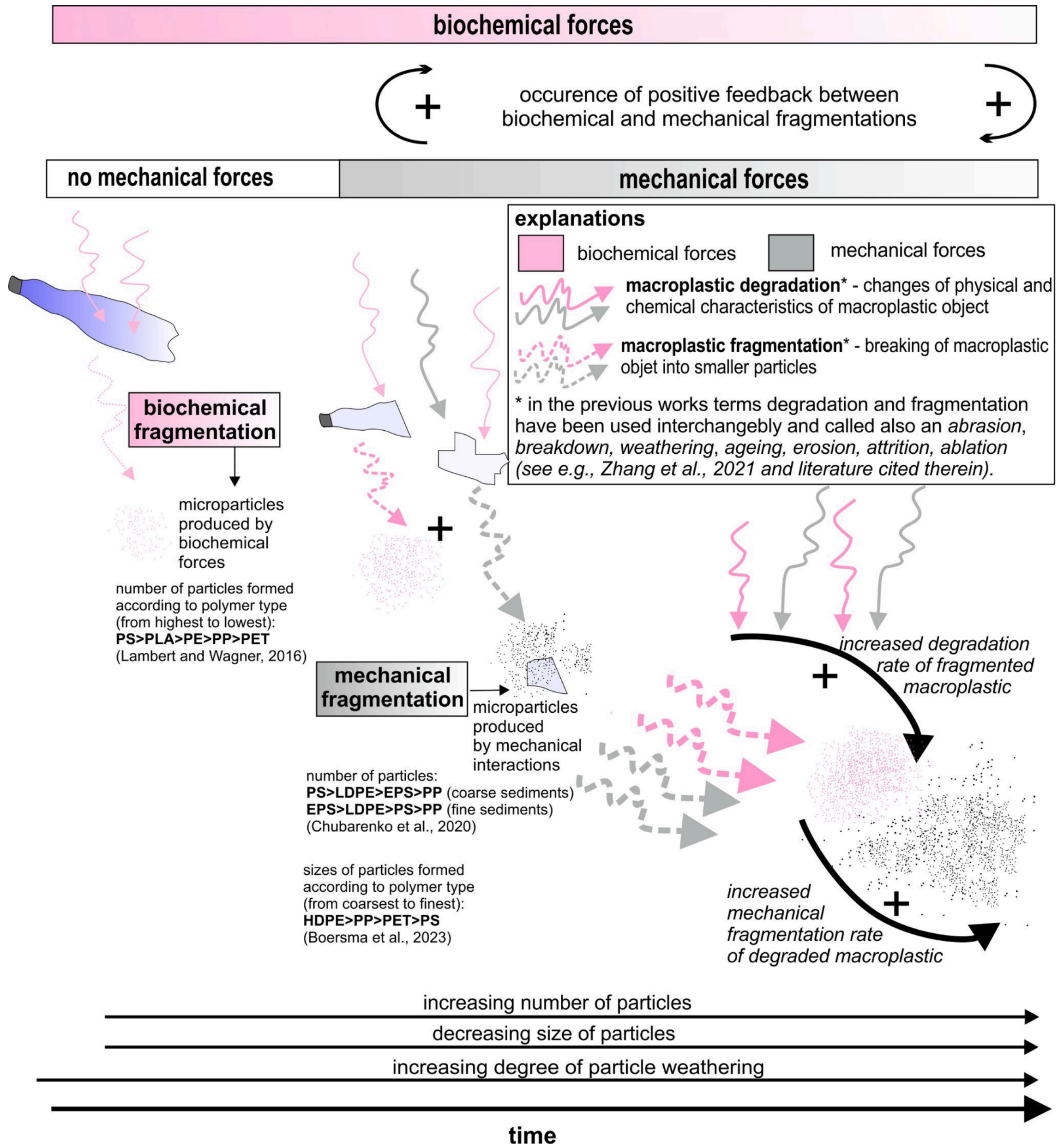


**Fig. 2.** Visualization of microparticles formed through biochemical and mechanical fragmentations and the positive feedback processes between them.

animals (e.g., biting), and anthropogenic infrastructure (e.g., ships, weirs). Thermal fragmentation refers to the disaggregation of macroplastic objects resulting from heating/cooling (e.g., sunlight, wildfire). The degradation and fragmentation of plastics through thermal forces alone require high temperatures (Chamas et al., 2020; Dimassi et al., 2022), which rarely occur in the ambient riverine environment; thus, in this paper, thermal forces are treated as accelerators for other types of degradation (see, e.g., thermal photo-oxidation in Dimassi et al., 2022).

### 2.1. *Intrinsic controls of macroplastic fragmentation*

Information on intrinsic controls was extracted from the existing literature on macro- and microplastic fragmentation (Boersma et al., 2023; Chamas et al., 2020; Chubarenko et al., 2020; Gerritse et al., 2020; Song et al., 2017; Sorasan et al., 2022; Sun et al., 2022) and is summarized in Fig. 3. The existing literature indicates that the potential for macroplastic fragmentation resulting from the intrinsic properties of macroplastics is a function of the plastic polymer composition, degree of previous weathering (see the y-axis in Fig. 3), and surface area-to-mass ratio of the macroplastic item (Chamas et al., 2020) (see the x-axis in Fig. 3).

#### 2.1.1. *Polymer type*

The polymer type (Boersma et al., 2023; Chubarenko et al., 2020; Lambert and Wagner, 2016) and degree of its previous weathering (Boersma et al., 2023; Sun et al., 2022) control the physical and chemical characteristics of plastics. The pathways leading to biochemical fragmentation differ between polymers with carbon backbone (PE, PP, PS and PVC) and these containing heteroatoms in their main chain (PET and PU). The biochemical fragmentation of the PE, PP, PS and PVC is preferentially initiated by photo-oxidation and followed by biodegradation, whereas PET and PU fragmentation is initiated by hydrolysis and continued by photo-oxidation, and biodegradation (Gewert et al., 2015). It is however important to note that several degradation pathways might take place simultaneously and that additives added to commercial polymers can modulate their fragmentation potential (for details see

**Table 1**
Summary of existing laboratory experiments on macroplastic fragmentation.

| Reference | Experiment details (details of polymer analysed; duration) | Types of fragmentation measured (biochemical, mechanical); Unit | Results |
|---|---|---|---|
| Chubarenko et al., 2020 | Laboratory experiment; PP (200 g), LDPE (200 g), PS (200 g), EPS (50 g) (2 × 2 cm quadrats) mixed by 24 h with water and sediment (four grain-sizes) | Mechanical; Number and mass of microparticle formed (within 20 L of water with 40 kg sediments) | Number of coarse microplastic (0.5–5 mm) formed (per 20L of water + 40 kg sediments):<br>• **fragmentation by large pebbles** (4.5–6 cm): 1.1 × $10^6$(**PS**), 3.6 × $10^4$(**LDPE**), 2.0 × $10^4$(**EPS**), 5.5 × $10^2$(**PS**),<br>• **fragmentation by small pebbles** (1.0–1.8 cm): 3.2 × $10^4$(**LDPE**), 1.9 × $10^4$(**PS**), 3.9 × $10^3$(**EPS**), 0.58 × $10^2$(**PS**),<br>• **fragmentation by granules** (3.0–4.0 cm): 4.5 × $10^3$(**EPS**), 2.5 × $10^3$(**LDPE**), 0.44 × $10^3$(**PS**), 0.14 × $10^2$(**PP**),<br>• **fragmentation by sand** (1.0–1.5 cm):4.9 × $10^3$(**EPS**), 1.4 × $10^2$(**PS**), 1.0 × $10^2$(**LDPE**), 0.72 × $10^2$(**PP**), |
| Lambert and Wagner, 2016 | Laboratory experiment; PP, PET, PE, PLA, PS (1 × 1 cm quadrats, 2.1 $cm^2$ film/sheet,pellets); 0.4 $cm^2$, 0–112 day | Biochemical;Number of microparticle formed (per 1 ml of water) | Number of microparticles and nanoparticles formed (per 1 ml):<br>• in **2–60 µm size range**, was: 92.5 × $10^3$(**PS**), 61.8 × $10^3$(**PLA**), 46.3 × $10^3$(**PP sheet**), 39.6 × $10^3$(**PE pellet**), 26.4 × $10^3$(**PP pellet**), 25.1 × $10^3$(**PET**), 24.3 × $10^3$(**PP film**);<br>• **in 0.6–18 µm size range** was; 11.6 × $10^6$(**PLA**), 10.3 × $10^6$(**PP pellet**), 9.9. × $10^6$(**PS**), 9.8 × $10^6$(**PP film**), 9.4 × $10^6$(**PET**), 8.9 × $10^6$(**PP sheet**), 8.0 × $10^6$(**PE pellet**)<br>• **in 30–2000 nm size range** was 6.4 × $10^8$(**PS**), 5.3 × $10^8$(**PLA**), 3.4 × $10^8$ (**PE pellet**), 1.8 × $10^8$ (**PP film**), 1.7 × $10^8$ (**PET, PP pellet**), 1.5 × $10^8$ for (**PP sheet**). |
| Song et al., 2017 | Laboratory experiment; PP, PE and EPS (pellets). Two months of mechanical fragmentation followed by 2,6 and 12 months of biochemical fragmentation. | Mechanical, Mechanical + Biochemical<br>Number of microparticle formed (per 60 ml bottle) | The 12 month exposition to UV irradiation increased the number of microparticles formed by 2 month of mechanical fragmentation from 8.7 to 20 for **PE**, from 10.7 to 6084 for **PP** and from 4222 to 10,501 for **EPS**. |
| Gerritse et al., 2020 | Laboratory experiment using 350 L mesocosm; a variety of conventional biodegradable and thermoplastics, 378–426 days | Biochemical fragmentation, Weight loss (%) per year | Weight loss per year reached ( %) was:<br>• **the highest (7–27 %)** for object built with compostable polymers and PLA<br>• **lower (3–5 %)** for object built with polyster backbone polymers (PET, PU)<br>• **the lowest (<1 %)** for polymers with a backbone with single "C–C" carbon bonds (PS, PP, PE) |
| Reineccius et al., 2023 | Laboratory experiment; HDPE, PP, PS, PET, PVC (pellets) in three water environments with different salinity. Fragmentation followed by 1, 2, 3, 4, 6 weeks and 2, 3, 4, 6, 9, 12, 15, 18 months | Mechanical (beach conditions) and biochemical (irradiation) | • **PP** as the least stable polymer among all tested polymer types.<br>• Size of the generated **PP** microparticles mostly below 10 µm.<br>**PS** yellowed after three months and intensified during weathering.<br>• Weight loss after 18 months:<br>• **PP** mass loss 5135.45 mg/L in most salinated water. |

Gewert et al., 2015; Dimassi et al., 2022). This may cause different rates of biochemical fragmentation for the plastic products built from the same polymer type in a given environments and control chemicals and metabolites released to environment during this process (Maga et al., 2022). Existing laboratory experiments showed that the rate of plastic fragmentation (understood as the number of produced particles or macroplastic item mass loss) was the highest for rigid (PS) or expanded polystyrene (EPS) and lower for low-density polypropylene (LDPE), polypropylene (PP) polyethylene (PE), and polyethylene terephthalate (PET) (Table 1; Fig. 3). The fragmentation of PS and EPS polymer types was identified as the highest in experiments on mechanical (Boersma et al., 2023; Chubarenko et al., 2020; Song et al., 2017) and biochemical fragmentation (Lambert and Wagner, 2016; Song et al., 2017). Some experiments documented, for example, that rate of mechanical fragmentation (measured as the item mass loss) is 1000–10,000 higher for PS and EPS than it is for PP polymer (Chubarenko et al., 2020). It was also indicated that mechanical fragmentation resulted from macroplastic interactions with coarser sediments (pebbles), producing 5–145 times more microparticles than fine sediments (sand), with the value of these difference being highly dependent on the polymer type (143× PS, 145× LDPE, 5× EPS, and 25× PP (Chubarenko et al., 2020). These observations provide an interesting background for the further quantification of riverine macroplastic fragmentation in rivers with coarse- and fine-grained bed (see Liro et al., 2022). It was also experimentally documented that microparticles formed via EPS and PS polymer fragmentation have smaller sizes than those released from PP and PET, with the largest formed from HDPE plastic (Boersma et al., 2023). Numerous riverine macroplastic waste items (e.g., cups, meat trays, plastic cutlery and straws, building insulation) are built from these fragmentation prone polymers (EPS, PS) (González-Fernández et al., 2021; Plastic Europe 2021; Tasseron et al., 2023). Gaining field-based information on their fragmentation rates seems to be especially important for our further understanding of the risks resulting from riverine macroplastic pollution. To describe consequences of fragmentation of different types of riverine macroplastics waste, we introduce the term *plastic footprint* which reflects the amount (mass or number) of plastic microparticles relased to the environment during its presence in the given river type (e.g., mountain vs. lowland river) by a given period of time (e.g., year). Future field and laboratory experiments Section 2.2 (see Table 2) can calculate such *plastic footprint* for common macroplastic waste objects to provide quantitative information for society and industry on the risk resulted from their disposal in river environments. Such information can be also useful for calibrating numerical models of microplastic formation in the environment (Boersma et al., 2023) and evaluation of the related risks (Maga et al., 2022).

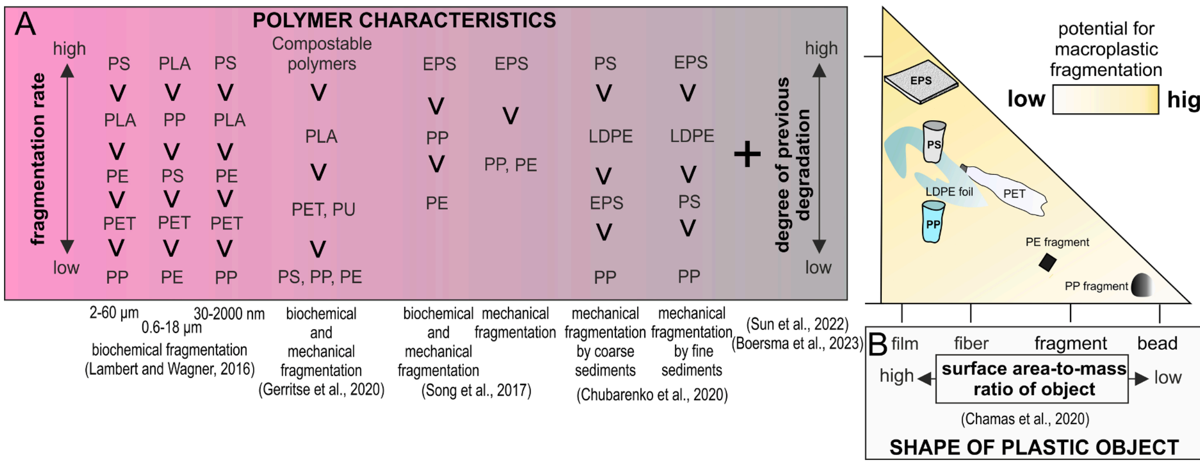


**Fig. 3.** The synthesis of the effects of intrinsic properties of macroplastic on its fragmentation potential. Macroplastic fragmentation potential are conceptualized as a function of polymer resistance to biochemical and mechanical fragmentation (based on experiments conducted by Lambert and Wagner, 2016; Song et al., 2017; Chubarenko et al., 2020; Gerritse et al., 2020 for details see Table 1) and degree of its previous degradation (Sun et al., 2022; Boersma et al., 2023) (y-axis) (A), and shape of plastic object (Chamas et al., 2020) (x-axis) (B).

#### 2.1.2. *Degree of previous degradation*

As one of the intrinsic properties of macroplastic important for its fragmentation, we also considered the degree of its previous degradation (Boersma et al., 2023; Sorasan et al., 2022; Sun et al., 2022) (Fig. 3A). Previous experiments showed that aged plastics have a fragmentation rate three orders of magnitude higher than the virgin one (Sorasan et al., 2022). This effects is connected with the loss of some mechanical properties of macroplastic object resulting from its previous biochemical degradation (e.g., loss of tensile strength, increase of brittleness) (Boersma et al., 2023), which make them prone to further mechanical fragmentation (Sun et al., 2022). Moreover, the fragmentation of aged plastic releases more nanoparticles (Sorasan et al., 2022), which are particularly harmful for biota and human health (Leslie et al., 2022). Thus, the inclusion of the degree of riverine macroplastic weathering as one of the controls of fragmentation seems to be important, because rivers are frequently eroding floodplains, thus remobilizing sediments containing aged macroplastic waste dumped in these locations in the past. Future efforts should focus on detecting and managing such zones to avoid the input and accelerated fragmentation of aged macroplastics in rivers. Taking into account the fact that weathering makes macroplastic more brittle and thus, prone to smaller microparticle release (Boersma et al., 2023), special attention should be paid to the avoidance of input of weathered macroplastic into inundated channel zones where it can be mechanically fragmented (see Fig. 4).

#### 2.1.3. *Surface area-to-mass ratio*

Biochemical and physical processes able to fragment macroplastic items take place mostly on the surfaces of macroplastic objects (Chamas et al., 2020). The potential for fragmentation of macroplastic objects was reported to be the highest for thin-film- and fiber-shaped objects, which have the highest surface-area-to-mass ratios, giving them larger surface areas which can actively interact with biochemical and physical factors of plastic degradation (Chamas et al., 2020) (Fig. 3). For example, the complete degradation of film-shaped macroplastic objects having the volume (2.9 $cm^3$) was reported to be 260–1100 times higher (film; 1.8 ± 0.4 years,) than that of fiber-(465 ± 100 years) and bead-shaped (2000 ± 400 years) objects of the same volume and polymer type (see Fig. 7 in Chamas et al., 2020). There are numerous examples of riverine macroplastic waste with film shapes, which enter rivers as packaging, buildings, and agricultural litters. Such items are frequently trapped in obstacles present in the inundated parts of river channels (e.g., boulders, wood jams) (Liro et al., 2022, 2023) or riparian vegetation (Cesarini and Scalici, 2022), providing them with ideal exposure to both mechanical (via water movement, wind, rain) and biochemical factors of fragmentation (via photo-oxidation) (Fig. 4).

As we illustrated in Fig. 3, intrinsic properties can bidirectionally interact with each other, enhancing or reducing potential for macroplastic fragmentation. For example, film shape object, having a high surface-area-to-mass ratio, can compensate for its low fragmentation potential resulting from high polymer resistance to fragmentation (e.g., HDPE, PP), and vice versa, the fragmentation of an object built with a polymer having high degradation potential (e.g., EPS or PS) can be reduced due to its compact shape. Taking into account a very wide range of reported differences in plastic fragmentation rates resulting from different polymers (e.g., up three to four orders of magnitude, Chubarenko et al., 2020) (see Table 1) and shapes (e.g., up to three orders of magnitude, Chamas et al., 2020), the degree of such compensation can be potentially very high.

### 2.2. *Effects of extrinsic controls on riverine macroplastic fragmentation*

Our conceptualization illustrates different intensities of biochemical and physical fragmentation between the inundated and non-inundated zones of perennial and intermittent rivers channels. These differences result from the changing influence of factors controlling these processes. The most important difference between the inundated and non-inundated parts of river channels is presence of water and sediment transport, which favors mechanical fragmentation and limits potential for biochemical fragmentation (by photo-oxidation) (Fig. 4). We also assume that potential for biochemical fragmentation may be regulated by the macroplastic transport mode because of different levels of exposure of differently transported and stored macroplastics to UV radiation and oxygen (Fig. 4B).

#### 2.2.1. *River hydromorphology*

In the inundated parts of perennial rivers (transporting water throughout the whole year), mechanical fragmentation is hypothesized to be dominant because of the chronic potential for mechanical collision of transported and stored macroplastics with water and sediments (Fig. 4A). Perennial rivers in populated areas are also frequently utilized by humans for navigation, recreation, and other purposes (e.g., dams, water extraction), which can favor the mechanical interaction of macroplastics with human infrastructure (e.g., with vessels, electric dam turbines, weirs). The potential for biochemical fragmentation in inundated parts of perennial river channels is generally reduced by the presence of water, which limits UV irradiation and oxygen exposure,

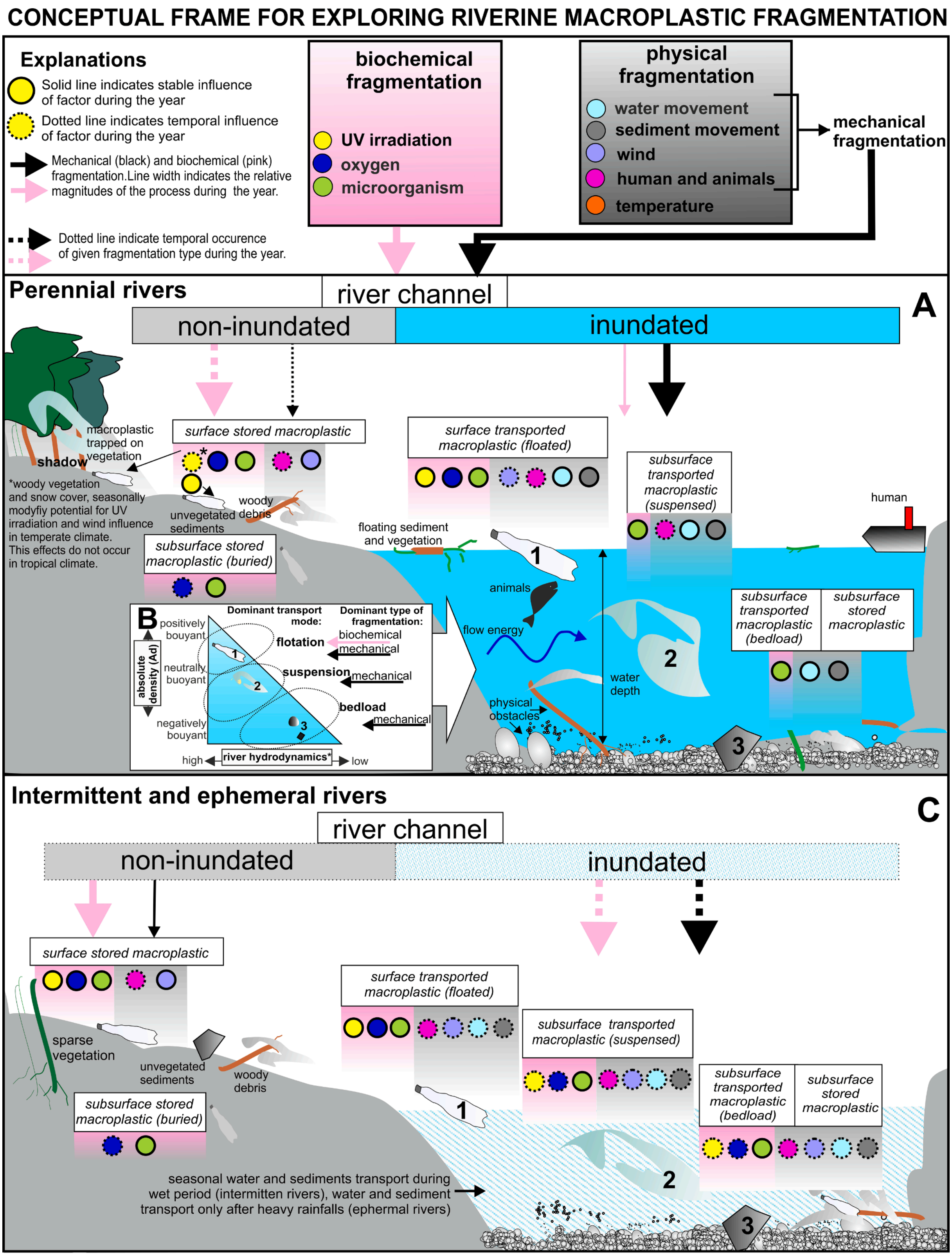


**Fig. 4.** The conceptual frame illustrating the intensity of biochemical and physical forces governing processes of macroplastic fragmentation in rivers. The frame structures differences between these two types of fragmentation in the inundated and non-inundated parts of the river channel for perennial (A) and intermittent rivers (C). The relationship between the absolute density of macroplastic objects and river hydrodynamics as controls of the dominant transport mode of macroplastic (B) is based on Russell et al. (2023). The provided numbers 1 (flotation) (absolute density < water density), 2 (suspension) (absolute density ~ water density), and 3 (bed-load) (absolute density > water density) visualize different transport modes of macroplastic debris in flowing water. The relative intensity of biochemical and physical fragmentation is indicated by the arrows' widths. The importance of given factors of fragmentation is visualized by circle sizes.

representing the main drivers of biochemical fragmentation (Andrady, 2015). Only macroplastic transported in flotation can be influenced by UV irradiation and oxygen in similar ways like those stored in non-inundated part of the river channel (Fig. 4A). Water penetration by UV irradiance is highly dependent on location and water characteristics (e.g., dissolved and suspended sediment concentration) and is typically substantially reduced in water deeper than a few meters (Dunne and Brown, 1996). Thus, macroplastics transported in suspension and as a bedload in most perennial rivers can be fragmented mostly through mechanical forces (Fig. 4A and B). Only in the very shallow river waters transporting clear water a potential for UV irradiation and related fragmentation exists. The mode of transport of each sediment transported in rivers (including plastics) is ultimately controlled by river hydrodynamics and sediment particle characteristics (see Kuizenga et al., 2022; Valero et al., 2022; Russell et al., 2023). The dominant transport mode of a macroplastic can be precisely evaluated using absolute density (see Russell et al., 2023) (Fig. 4B). For example, air-filled plastic bottles, independent of the density of the polymer types they are composed of, will be transported in river channels in flotation because of their low net density. The same type of bottle filled with water or sediments will be transported in suspension or as a bedload (see Fig. 13A in Russell et al., 2023). It is important to highlight here that different transport modes of macroplastics in flowing water also modulate the intensity of macroplastic interactions with water, sediments, and riverbeds. For example, the same macroplastic object can be transported in suspension and as a bedload, respectively, in fast-flowing rivers with steep channel slopes and in slow-flowing rivers with gentle channel slopes. The modes of transport can also vary within the same river reach for different flow conditions, with high potential for transport during floods and lower potential in normal conditions (van Emmerik et al., 2023). It is important to note that the mode of transport of the same macroplastic object can also dramatically change locally, for example, between different bed morphologies and channel patterns. The example can be a river with a steep pool sequence, as is common in mountain rivers (Wohl, 2010). Such a bed morphology has hydrodynamics which are highly variable locally with fluctuations between shallow, fast-flowing step zones and deeper, slower-flowing pool zones (Wohl, 2010). Thus, river hydrodynamics, together with the buoyancy of macroplastic waste objects, are important and unexplored factors determining the intensity of macroplastic interactions with river water, sediments, and beds. Taking into account the fact that river hydrodynamics are highly variable in both time and space, there is a need for future field experiments to directly quantify the intensity of macroplastic fragmentation for macroplastic items with different fragmentation potential (Fig. 3) in different flow conditions and for different hydromorphological types of rivers (see, e.g., Liro et al., 2022). Artificial modifications of river hydromorphology (e.g., through channel regulation, bed and bank construction), can also be investigated in the context of riverine macroplastic fragmentation in future works.

River channel hydromorphology, as a control of the physical fragmentation of macroplastics, seems to be less important in the case of intermittent and ephemeral rivers which transfer water and sediments only periodically (Fig. 4C). Such flow events in intermittent or ephemeral rivers are frequently triggered by heavy rainfall and have high energy capable of transporting coarse sediments (Martín-Vide et al., 1999). As discussed in the previous section, such a phenomenon can effectively fragment macroplastic present in a river channel (see Fig. 3). Intermittent rivers can also transport products previously subjected to biochemical fragmentation during such events.

#### 2.2.2. Climate

In non-inundated parts of perennial rivers and within the whole channel zone of intermittent rivers, biochemical fragmentation is hypothesized to be dominated because of exposure to UV irradiation and oxygen, and physical fragmentation can occur mostly due to wind action (Fig. 4). Depending on the local setting (e.g., the surrounding vegetation types, human infrastructure) and climate, the intensity and importance of a given fragmentation type will change. It may be interesting to experimentally compare biochemical fragmentation rates of the same macroplastic wastes in the non-inundated zones of rivers in different climatic zones in future works (see e.g., Delorme et al., 2021).

Future works can also explore effects of macroplastic colonization by biota as factor modulating biochemical and mechanical fragmentation rates of riverine macroplastic. Recent evidences suggest a positive feedback mechanism between colonization and degree of macroplastic degradation in perennial rivers (Gallitelli et al., 2023). However, the pathway of this process in perennial and intermittent rivers in different climates is unknown.

## 3. Future outlook

Our theoretical framework aims to provide a guide for the future exploration of riverine macroplastic fragmentation. We identified (i) macroplastic item properties that impact its fragmentation, (ii) the relevant biochemical and mechanical fragmentation processes, and (iii) their relative importance between inundated and non-inundated parts of perennial and intermittent rivers. Our conceptualization can support planning of future experimental and modelling work aimed at the direct quantification of macroplastic fragmentation rates in rivers. Such information is currently mostly unavailable for rivers (Delorme et al., 2021), but is of crucial importance for understanding secondary micro- and nano-plastic production in rivers, the transfer of these harmful particles throughout the natural environment, and the imposed risks. Based on our conceptual frame (Fig. 4), we hypothesize that:

- (H1) inundated part of the perennial river channels provide conditions that particularly accelerate mechanical fragmentation of macroplastic resulting from its mechanical interaction with water, sediments and riverbed,
- (H2) the rate of biochemical fragmentation in non-inundated part of perennial rivers is modulated by seasonal changes of vegetation covers and snow,
- (H3) in the intermittent rivers macroplastic have similar potential for biochemical fragmentation in temporarily inundated and non-inundated parts of river channel, and
- (H4) that intermittent and ephemeral rivers have generally higher potential for biochemical fragmentation than perennial rivers.

In Table 2 we propose designs of field experiments that allow to test these hypothesis in future works. Moreover, we highlights a need for (i) future experimental quantification of the rates of mechanical fragmentation of common macroplastic items between lower-energy lowland rivers and higher-energy mountain rivers, (ii) the evaluation of the importance of artificial modifications (e.g., channelization, dams) of river physical characteristics on the spatial and temporal trajectories of mechanical fragmentation of macroplastics, (iii) the detection of compartments of fluvial systems (e.g., geomorphological forms, reach types, catchments, zones of fluvial systems) operating as generators and sinks of secondary micro- and nanoplastics (see, e.g., Liro et al., 2022), and (iv) the evaluation of the downstream dispersal of secondary microplastics from such hotspots. Such data will allow for an evaluation of the amount of secondary microparticles formed during the macroplastic's journey throughout the river. Information on this *plastic footprint* for a given type of macroplastic waste is a first step in the planning of its future mitigation.

**Table 2**
Examples of proposed future field and laboratory experiments on macroplastic fragmentation.

| River type | River zone | Hypothesis | Design of proposed experiment |
|---|---|---|---|
| Perennial rivers | Inundated part of river channel | (H1a) Intensity of mechanical fragmentation of macroplastic is larger in the inundated part of the river channel than in the non-inundated one, (H1b) mechanical fragmentation rate is higher in high-energy rivers with coarse bed sediments (mountain stream) than in low-energy rivers with fine-grained bed (see also Liro et al., 2022) | • (H1a, b) Comparison of surface characteristics (for methods see e.g., Delorme et al., 2021), tensile properties (for methods see e.g., Williams and Simmons, 1996) and mass loss (for methods see e.g., Gerritse et al., 2020) of the same macroplastic object placed in the inundated and non-inundated parts of river channel.For objects transported in the inundated part of river channel trackers techniques (e.g., GPS, RFID, radio transmitters, printed items) should be additionally use to found them (for methods see Liro et al., 2022) . |
| | Non-inundate part of river channel | (H2a) Intensity of biochemical fragmentation of macroplastic stored in non-inundated part of river in temperate climate is modulated by presence of vegetation cover and its type, (H2b) it's seasonal changes and (H2c) temporal occurrence of snow cover. Occurrence of snow cover also temporarily decrease mechanical fragmentation resulting from wind (especially important for soft macroplastic object e.g., plastic foils) | • (H2a) Comparison of the above (H1) characteristics of macroplastic object placed in vegetated and non-vegetated parts of non-inundated zone of river.<br>• (H2b) Comparison of the above characteristics of macroplastic between places overgrown by seasonally changing (e.g., deciduous forest) and stable vegetation (e.g., coniferous forest) within the same location.<br>• (H2c) Comparison of the above characteristics of macroplastic between seasons with and without snow cover.<br>For planning the fieldwork design see e.g., Delorme et al., 2021. |
| Intermittent and ephemeral rivers | Inundated part of river channel | (H3a) Intensity of biochemical fragmentation in the inundated and non-inundated part of intermittent rivers is similar, (H3b) intensive mechanical fragmentation occurs during temporal water and sediment flows | • (H3a) Experimental design the same like for H1<br>• (H3b) Experimental design the same like for H1 |
| | Non-inundated part of river channel | (H4) Intensity of photo-oxidation will be higher in non-inundated part of intermittent rivers than for perennial one, because of higher and more continuous exposition to sunlight (sparse vegetation or lack of vegetation, lack of snow cover) | • (H4) Comparison of results obtained during testing H2 with analogical data collected on intermittent and ephemeral rivers. |

## Author contributions

**ML** conceptualized paper idea, wrote the original draft, and created original figures; **AZ** reviewed the literature and contributed to writing the original draft and the figures' preparation; **TvE** took part in writing and revising the manuscript and figures.

## 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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