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Plastic as a Sediment – A Universal and Objective practical solution to growing ambiguity in plastic litter classification schemes

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Abstract

The universal and growing challenge of inconsistency and ambiguity in plastic classification schemes restricts our ability to predict plastic routing, degradation, and accumulation in all environments worldwide. Global plastic production has risen exponentially, reaching approximately 9,200 million tons between 1950 and 2017. Of this, an estimated 5,300 million tons have been discarded, with a significant fraction mismanaged and entering the natural environment. Plastics are pervasive, found in nearly every terrestrial and marine environment, and their durability ensures that they can persist in the environment for thousands of years, posing escalating ecotoxicological and environmental risks. To meaningfully address plastic distribution, pathways, and the impact it has, we need a clear, universally applicable classification scheme. Whilst there have been many calls to action from the community, we do not yet have a solution offered that facilitates universal understanding through its applicability. Here we propose treating plastic as sediment, such that we may employ the well-established principles and methodologies of sedimentology within its widely applicable framework for understanding and classifying particles. By applying sedimentological techniques to plastics, we developed a classification scheme to objectively describe plastic by its fundamental sedimentological characteristics that are known to correlate with particle behavior and distribution in the environment., i.e., size, shape, density, and material properties. It centers on objective observation before classification and interpretation, recognition of spatial and temporal changes, and an adaptable and flexible framework that can adapt to the complexities of plastic characteristics and research questions. As the classification scheme isolates each physical variable seen in plastic, through using it, we will be better able to understand how plastic characteristics influence their environmental behavior. Whilst the use of this scheme will be primarily beneficial in assessing source-to-sink routing, transport processes, and accumulation tendencies of plastic objects and particles, its potential impact extends beyond this. It has the capacity to enhance environmental monitoring and management strategies through cross-disciplinary and cross-regional data comparisons and exchanges, which will benefit a broad range of stakeholders interested in understanding and managing plastic pollution.

Introduction

Plastics, or synthetic polymers, are extremely versatile materials that are commonly synthesized from fossil hydrocarbons (Thompson *et al.,* 2009), and designed for many products and purposes (Nkwachukwu *et al.,* 2013). Recent decades have seen the rising popularity of plastic lead to an exponential increase in global production of approximately

9,200 million tons of plastics between 1950 to 2017, an estimated 5,300 million tons of which has been discarded and may enter the environment if mismanaged (Geyer *et al.,* 2017, 2020; UNEP, 2021). Unfortunately, on a global perspective, mismanagement of plastic is common and plastic litter has been found in almost every terrestrial and marine environment on Earth (e.g. Andrady, 2011; Zylstra, 2013; Eriksen *et al.,* 2014; Pham *et al.,* 2014; Wagner *et al.,* 2014; Woodall *et al.,* 2014; Peeken *et al.,* 2018; Allen *et al.,* 2019; Bergmann *et al.,* 2019; Meijer *et al.,* 2021). This is concerning because there is growing evidence for ecological harm from plastics (e.g. Wright *et al.,* 2013; Cole *et al.,* 2015; Gall & Thompson, 2015; Kühn *et al.,* 2015; Lusher *et al.,* 2015; Bakir *et al.,* 2016; Wang *et al.,* 2016; Galloway *et al.,* 2017), and many plastics are designed to be long-lasting, so items in the environment may persist for up to thousands of years (Gregory & Andrady, 2003; Chamas *et al.,* 2020; Turner *et al.,* 2021). Consequently, plastics and its residuals have become a ubiquitous component of natural environments and will likely turn into an integral element of the depositional record of the Anthropocene, hence posing substantial ecotoxicological, structural, and environmental risks to be faced by future generations (Waters *et al.,* 2016; Zalasiewicz *et al.,* 2016; Rillig *et al.,* 2021). It is important to recognize these products from their origin (source) to their final resting place (sink) and a number of studies across multiple disciplines have focused on identifying this routing, as well as estimating global plastic waste budgets in natural environments (Pruter, 1987; Browne *et al.,* 2011; Eriksen *et al.,* 2014; Woodall *et al.,* 2014; Jambeck *et al.,* 2015; van Sebille *et al.,* 2015; Geyer *et al.,* 2017; Koelmans *et al.,* 2017; Lebreton *et al.,* 2017, 2019; Lau *et al.,* 2020; Range et al., 2023).

Sediment, and pollution therein, is a significant part of many disciplines besides sedimentology, such as soil science, environmental science, hydrology, geomorphology, archaeology, urban planning, and many more. The nature of sediment research across these disciplines is multi-faceted and includes studying how it interacts with waterbodies, the contaminants that the sediment contains, sediment composition, as well as the layers that the sediment forms, and its part in landscape evolution. Therefore, principles rooted in sediment studies, all connected by sedimentology, are essential for unifying diverse environmental concepts. However, the integration of plastic pollution into these interdisciplinary discussions is insufficient, largely due to a lack ofconsistency in how it is classified, described, and recorded (Hidalgo-Ruz *et al.,* 2012; Filella, 2015; Van Cauwenberghe *et al.,* 2015; Hartmann *et al.,* 2019; Range et al., 2023), therefore most studies are limited to discipline-restricted, regional, or case specific methodologies or classifications (e.g., OSPAR, 2010; Van Emmerik *et al.,* 2020). Unification of plastic classifications is a widely recognized challenge and there have been many calls for harmonization (e.g., Hartmann *et al.,* 2019; Vriend *et al.,* 2020; Weber *et al.,* 2022). Much of the challenge in determining a consistent nomenclature and classification of plastic stems from the diversity, and complexity of their morphology and properties (IOS, 2013; GESAMP, 2015; SAPEA, 2019). Additionally, discrepancies have arisen between plastic classification schemes because different studies have had varying study objectives, so may have been discipline- or case-specific (e.g. Dris *et al.,* 2016; Arthur *et al.,* 2009; Bermúdez and Swarenski 2021), so the focus, definitions, and techniques have varied accordingly. However, this doesn't account for all discrepancies as even amongst internally consistent studies, the findings differ depending on if the item classification is executed via item category, item material, or item function (Vriend *et al.,* 2020). Challenges include: i)even if past item function is used consistently for classification, an item such as a bottle may be any size with any property so has limited use when seeking to understand the hydromechanics of the bottle (Vriend *et al.,* 2020); ii) plastic studies commonly have at least one miscellaneous "bucket" category such as "unidentifiable", "film", or "fragment", which are ambiguous, broad, and set to grow as plastic degradation continues in the environment. Therefore, an objective, unified approach would enable for better classification of plastic objects in the environment, in turn contributing to better predicting the environmental behavior of plastic and the global distribution of plastic litter (e.g. Enders *et al.,* 2019; Filella, 2015).

Sedimentology has well-established principles and methodologies that can serve as the framework for plastic research offering significant and exciting potential to unify our understanding of polluted environments (Göral *et al.,* 2023). By considering plastic as a sediment, we may in turn expand and integrate our understanding of plastic-related processes in the sedimentological framework. Applications for classifying any plastic particles or objects as sediment include significant potential for assessing source to sink routing, transport processes, and accumulation tendencies of such materials. Sedimentology is structured from a quantitative and objectively consistent framework that includes well established schemes for the classification of sediment, such as descriptions of size and shape of individual sediment grains (Wentworth, 1922; Passega, 1957; Boggs, 2009). From this, we can derive the physical parameters that are drivers of the cause-and-effect chain of processes through an environment, which is underpinned by fundamental physics (e.g., Reading, 1996 and references therein), and more recently, modelling techniques (Ara Rahman & Chakrabarty, 2020). From understanding the individual particle behaviors, we can understand their organization at different scales, extending to the evolution of an entire sedimentary system (e.g., aeolian, riverine, or marine environments). Sedimentology encompasses both the transport and deposition of sediment, as well as the deposit itself, allowing the origin and future of a sediment to be assessed at any point along its route. This enables the interpretation of long-term processes and trends, both past and future, for individual grains or entire landscapes on Earth and beyond (Collinson *et al.,* 2006 and references therein). Indeed, plastic in the environment is behaving like a sediment in that microplastics of different sizes and densities are found to occur in different sedimentary settings, indicating that their transport and accumulation relate to sedimentation (Hidalgo-Ruz *et al.,* 2012). Whilst there are reported challenges in linking plastic behavior to sedimentological principles (Chubarenko *et al.,* 2018; Khatmullina & Chubarenko, 2019; Waldschläger & Schüttrumpf, 2019), Göral *et al.,* (2023) demonstrates that microplastic behaviors do indeed align with sediment behavior on the Shields diagram. The Shields diagram is a tool to identify the critical conditions under which particles on a bed surface will start to be moved by fluid flow, linking particle size, fluid velocity, and bed shear stress (Shields, 1936), all crucial for predicting the behaviors of plastic in the environment (Göral *et al.,* 2023). As such, the fundamental framework for particle motion is universally applicable and may be related across engineered and natural materials (Enders *et al.,* 2019), but we need to be able to describe plastic materials objectively and consistently so that we can use these tools and understand plastic as sediment.

Elements of sedimentological classification such as grain dimensions (Zingg, 1953), or material density (Harris, 2020) may be directly applied from sedimentology to the study of plastic, however, plastic presents challenges that differ from natural sediment. For example, natural sediment is composed mainly of natural minerals, whereas plastic polymers present distinctive challenges in the range of complexity of their composition, requiring adaptations for how sedimentological techniques can be used for plastics. For example, the material composition combined with the shape complexity of many plastic items highlights the importance of holes, which extends beyond what we know of rock porosity. To illustrate this, a bottle with its lid on and full of air, will float, but with its lid off, it may collect water or sediment and sink. As such, introducing the 'hole'-concept into this classification is important because it captures unique aspects of plastics (of all scales) that affect their transport, degradation, and deposition in the environment, which are not sufficiently covered by parameters like density or polymer characteristics, therefore existing research has not yet fully demonstrated the importance of these aspects. We provide a more detailed and nuanced framework that will enable deeper insights into plastic behavior in a range of contexts by standardizing how we record plastic object characteristics, such that future studies may more objectively and systematically explore their sedimentological presentation.

In this paper, we use concepts of sedimentology to develop a future-proofed, quantitative, and objective plastic particle classification methodology. To achieve this, we focus on creating a classification scheme that is designed to apply to all plastic particles, regardless of their depositional or non-depositional status. We emphasize methodology and recommendations for field studies considering plastic in-situ, though our classification scheme remains applicable across all environmental contexts. As such, this classification will provide a foundational descriptive tool for scientists of all disciplines, helping to enhance the interconnectedness of individual studies and our united understanding. In this scheme, we account for the size, shape, density, and material properties of plastics, which contribute to their morphological and behavioral complexity. Importantly, this is not just another classification scheme, but a philosophically grounded solution to a long-standing challenge that makes meaningful headway towards an objective practical solution by reconnecting our human-made materials to natural systems. The approach outlined in this manuscript will improve comparability of predictive models, so that environmental monitoring studies can be more targeted and, allow researchers to undertake representative sampling and provide consistency across disciplines and latitudes (Kane & Fildani, 2021; Waldschläger *et al.,* 2022). Through using this unified classification scheme for data collection, the universal perception of global plastic pollution and its consequences will be better understood (Hartmann *et al.,* 2019; Kooi & Koelmans, 2019; Hapich *et al.,* 2022), with advantages spanning a multi-disciplinary and multi-regional scale (van Calcar & van Emmerik, 2019).

Background

Sedimentology, sediments, and sediment transport

In its classic sense, sedimentology is the study of natural sediment sources, movement, and accumulation in the environment. Our understanding of sedimentary processes contributes to successes in exploration, natural hazard risk assessments, and estimations of global carbon dioxide (CO2) budgets (Pettingill, 2004; Jakob, 2005; Galy *et al.,* 2007; Hage *et al.,* 2020). Processes considered in sedimentological transport and deposition may be explained with fluid dynamics models that predict grain mobilization at a given flow velocity in a given environment (e.g. Hjulström, 1936; Shields, 1936; Bagnold, 1979). These principles, enable sedimentologists to largely predict sediment transport type under specific flow conditions, where specific types of sediment are likely to be deposited, the scale of the sediment accumulation, its internal structure, and how that may change over time (Allen, 1965; van Rijn, 1993; Reading, 1996). The principles also work in reverse whereby the sedimentary deposits can be interpreted to provide insights into the processes that formed the deposits (Allen, 1971, 1985; Collinson *et al.,* 2006).

Sedimentologists commonly work at a large scale of application of these principles, i.e., the source to sink system whereby the sediment is eroded from the landscape and transported to an ultimate sink, or terminal resting place, such as the deep ocean (Castelltort and Van Den Driessche, 2003; Romans *et al.,* 2016; Schumm, 1977). Additionally, sedimentology can aid understanding far into both the past and into the future, e.g., the premise that a grain will break down into smaller grains, and the rate will depend on many factors including mineral hardness and environment. Therefore, sedimentological principles and techniques apply to both recent deposits in terrestrial and aquatic environments, as well as to ancient, often millions of years old deposits in the sedimentary rock record (Reading, 1996; Mutti *et al.,* 2009).

Sediment particle classification schemes

Sediment particle classification schemes have been developed to objectively highlight the important aspects of a particle in the environment that will influence, and in total determine, its hydrological behavior over time and space. Here, we focus on natural sediment schemes that have been developed to describe and classify siliciclastic sediments that are mainly composed of minerals, such as quartz or feldspar, and fragments of eroded rock known as lithic clasts. Siliciclastic sediment particle classification schemes are the most directly relatable to plastic particles, hence contain the most adaptable components to plastic classification.

Density

The most common natural particles to be considered in sediment transport processes are quartz (2.65 g/cm^3), clay (i.e., Montmorillonite 1.7-2.0 g/cm^3 and Kaolinite 2.16-2.68 g/cm^3), and biologically created particles such as organic matter (0.9-1.3 g/cm^3) and calcite (2.71 g/cm^3) (Duda & Rejl, 1990). Biologically created particles may also include wood, algal debris, corals, and bivalves. Most empirical studies base their transport model parameters on quartz's density, which is 2.65 g/cm^3, and the presumption of a spherical shape for the purpose of practical simplicity (Lofty *et al.,* 2023), though we do understand that grain shape affects bedload transport (Deal *et al.,* 2023).

Grain size

The term 'grain size' refers to the length of individual particles, which may be defined by its long (ℓ), intermediate (i), and short (s) axes. This distinction becomes particularly helpful when analyzing non-spherical shapes and the measured length must be reported. The Udden-Wentworth scale is a widely used grain size scale in sedimentology (Udden, 1914; Wentworth, 1922) (Fig. 1). Size boundaries are categorized into the Wentworth size classes that are delimited by integers of the grain size parameter Phi Φ is where Φ is calculated as $\Phi = -\log_2(D)$, with D representing the grain diameter in millimeters (mm). Thus, the size boundary of each Wentworth size class is twice as large as the preceding class.

Millimeters (mm)		Micrometers (μm)	Phi (ϕ)	Wentworth size classes		Rock type
	4096		-12.0	Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0	Cobble		
	64		-6.0	Pebble		
	4		-2.0	Granule		
	2.00		-1.0	Very coarse sand	Sand	Sandstone
	1.00		0.0	Coarse sand		
1/2	0.50	500	1.0	Medium sand		
1/4	0.25	250	2.0	Fine sand		
1/8	0.125	125	3.0	Very fine sand		
1/16	0.0625	63	4.0	Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0	Medium silt		
1/64	0.0156	15.6	6.0	Fine silt		
1/128	0.0078	7.8	7.0	Very fine silt		
1/256	0.0039	3.9	8.0	Clay	Mud	Claystone
	0.00006	0.06	14.0			

Figure 1 – The Udden-Wentworth scale for the size classification of natural sediments (modified from (Wentworth, 1922).

Grain shape

Particle shape is defined by three key properties: surface texture, form, and roundness (Barrett, 1980 and references therein) – (Fig. 2).

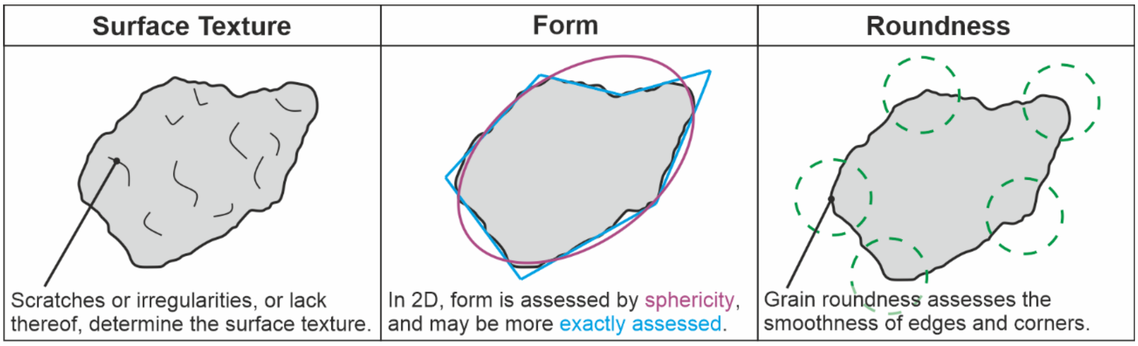


Figure 2 – Grain shape definition based on surface texture, form, and roundness. Modified from (Barrett, 1980).

1) The **surface texture** describes the microrelief on the surface of the grain such as scratches and cavities (Krinsley & Doornkamp, 1973; Mahaney, 2002), which are in the micrometer scale so commonly examined by microscopy techniques. More than 40 specific types of surface textures have been described such as V-shaped etch

pits, grooves or scratches, conchoidal fractures and abrasion features (Mahaney, 2002; Boggs, 2009). Most of these features are created by grain-to-grain interaction or collisions during transport or by abrasion through wind and water (Jackson & West-Thomas, 1994; Mahaney, 2002 and references therein).

2) The **form** of a grain is most widely described using the simple and illustrative scheme proposed by Zingg (1935). It uses the elongation (ratio of the intermediate (i) to long grain axis (ℓ)) and the flatness (ratio of the short (s) to intermediate (i) grain axis) to classify the particle as a disc, sphere, blade, or rod (Fig. 3).

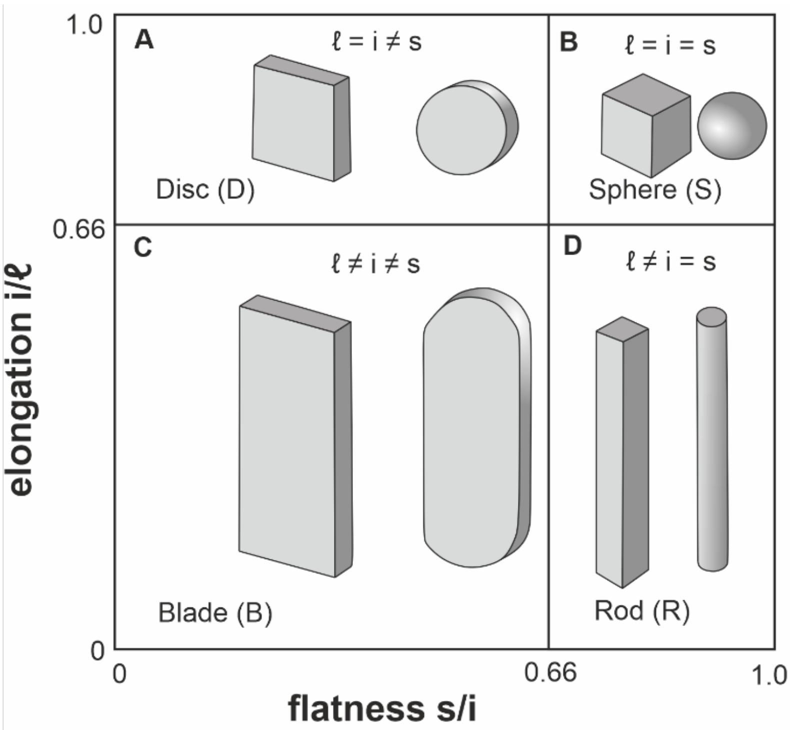


Figure 3 – A grain shape classification after (Zingg, 1935). Four different grain forms are identified based on the relation of the grain axes.

3) Grain **roundness**, which describes the sharpness or smoothness of grain edges is independent of the grain form. Surface texture is correlated with the more well-rounded particles being smoother in texture. Powers' (1953) scheme defines six grain roundness classes from very angular to well rounded (Fig. 4). It is one of the most widely used roundness scale schemes today and developed from previous schemes (e.g., Wadell, 1935; Russell & Taylor, 1937; Pettijohn, 1949).

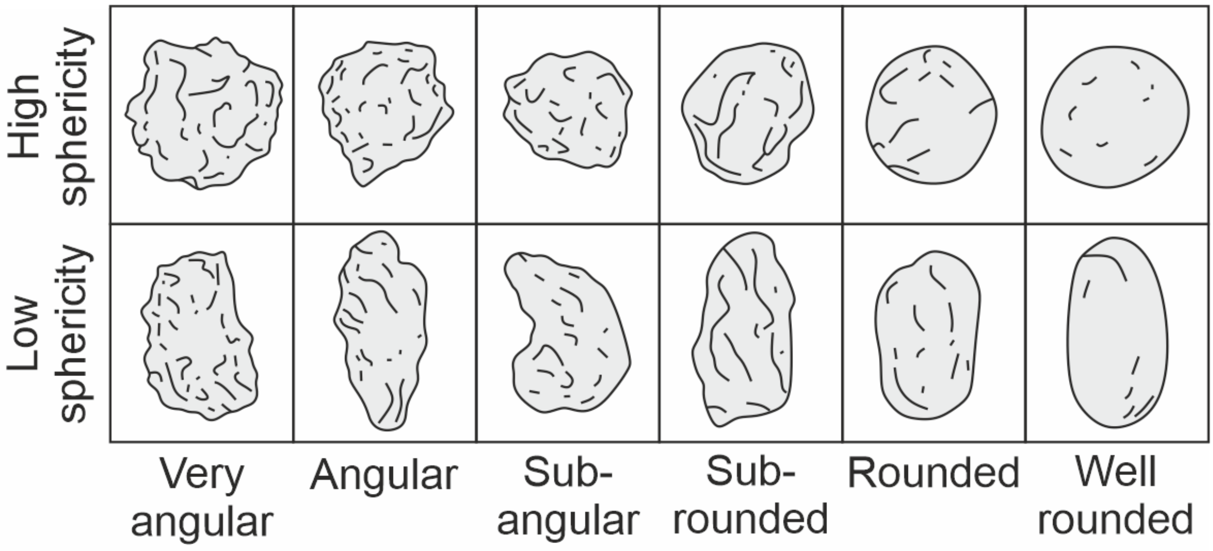


Figure 4 - Roundness classification scheme after Powers (1953). Roundness is independent of grain form and here described as correlative to grain texture, divided into six classes ranging from very angular to well rounded.

Particle properties and sediment transport

To understand the dynamics of sediment transport, i.e., erosion, transport, and deposition, we must understand numerous factors, which importantly include the physical characteristics of the sediment, as well as the dynamics of the fluid. The physical properties of a particle determines its settling or rising velocity, i.e., the rate at which a particle sinks, or rises, in a stationary fluid, primarily influenced by gravity, fluid viscosity, and the density, size, and shape of the particle. It is the balance of gravitational forces and fluid resistance (or drag) that determines these velocities, which are well understood for isolated, simply shaped particles, such as spheres (e.g., Stokes' Law, (Shearer and Hudson, 2008)). However, complex particles and particle clusters are more challenging due to variable fluid resistance caused by the complex particle shape, and perhaps its rotation, deformation, or particle interactions therein (e.g., Camenen, 2007; Ferguson and Church, 2004; Francalanci *et al.,* 2021; Zwanzig, 1964). Flow velocity directly impacts sediment transport dynamics in controlling which sediment is mobilized or deposited, which varies depending on the particle characteristics (Corrsin, 1961; Nezu, 2005; van Rijn, 1993). Increasing flow velocities combined with strong turbulence can lead to increased sediment mobilization and broader sediment dispersal, whilst decreasing flow velocities result in deposition and reduced turbulence (e.g., Eggenhuisen *et al.,* 2019; Hunt, 1954; Rouse, 1937). The bed shear stress is the force exerted on the sediment bed by a moving fluid and directly influences the threshold at which sediments start to move (Shields, 1936; Wilcock, 1996). The threshold is known as the critical shear stress at which they begin to move, either rolling, sliding, or becoming suspended in the fluid (Lee and Balachandar, 2012; Wilson, 1987).

Understanding sediment properties is essential for determining their behaviour in fluids and in nature, therefore, particle properties are crucial to our understanding of how plastics will mobilize through the wider environment.

Plastic particles, properties, and transport

The classification methods developed by the plastics research community offer valuable insights that can significantly enhance our understanding of the transport of plastic litter within sedimentologically centered studies. Here, we explore these methods to integrate their strengths with our approach.

Plastic classification schemes

Plastics are materials containing a high polymer i.e., a macromolecule which is composed of repeating monomers. The categorization of materials to the term plastics is unsettled and varies across different scientific disciplines. Hartmann *et al.,* (2019) proposed three criteria: (i) chemical composition, (ii) solid state, and (iii) solubility, which is how we define plastic material in this manuscript. Once an item is identified as plastic and allocated to its polymer group, it is typically further assessed by its size (e.g. micro or macroplastic), shape (e.g. fragment or fiber), and if possible, origin (e.g. primary or secondary) (e.g., Wagner *et al.,* 2014; Hartmann *et al.,* 2019). However, categorization of plastic litter typically lacks standardized definitions (e.g. Provencher *et al.,* 2020), such that nomenclature and size and shape classes are either not defined at all, or contrasting schemes are used throughout different studies (IOS 2013; Filella, 2015; Burns & Boxall, 2018; Hartmann *et al.,* 2019; Provencher *et al.,* 2020).

Polymer density

The most common plastic polymers range in density from 0.832 g/cm^3 to 1.58 g/cm^3 (Table 1 – collated from (Kooi & Koelmans, (2019), and Harris, (2020)). The most widely used plastic polymers include PE, PS, and PET (PlasticsEurope, 2020), and the incorporation of additives and fillers can also alter their densities. Much of the research and experimentation of plastics as sediment has developed around these main monomers (Chubarenko *et al.,* 2018; Russell *et al.,* 2023).

Density g/cm^3	Chemical name	Common example
0.83-0.92	Polypropylene (PP)	Bottle caps, rope
0.89-0.98	Polyethylene (PE)	Plastic bags
1.04-1.10	Polystyrene (FPS)	Floats, containers
1.02-1.16	Polyamide (Nylon)	Fishing nets, clothing

1.10-1.58	Polyvinyl chloride (PVC)	Plastic film
0.96-1.45	Polyethylene terephthalate (PET)	Plastic bottles, carpet, clothing
1.19-1.31	Polyvinyl acetate (PVA)	

Table 1 – Density (g/cm^3), chemical names, and examples of common plastic types collated from Harris (2020), and Kooi & Koelmans (2019).

Plastic particle size

The first plastic size classification scheme was introduced by Gregory & Andrady, (2003) who introduced the terms macro-, meso-, and microlitter to describe and classify marine debris. The class size boundaries were based on mesh sizes of commonly used sieves and encompassed plastic items in the size range of 63μm to 15 cm (0.63 to 150 mm), (Gregory & Andrady, 2003). Later studies adapted the terminology to macro-, meso-, and microplastics and extended it at the lower and upper ends by nano- and megaplastics respectively, such that this nomenclature now represents plastic size classes (e.g., Thompson *et al.,* 2004; Browne *et al.,* 2007; Moore, 2008; Arthur *et al.,* 2009; GESAMP, 2015; Hartmann *et al.,* 2019). However, despite a general consensus on the nomenclature, there remains no standardized agreement of the size boundaries of the different size classes (Filella, 2015; Burns & Boxall, 2018; Chubarenko *et al.,* 2018; Hartmann *et al.,* 2019). Size boundaries may be established based on the ability of specific organisms to ingest it (Bermúdez & Swarzenski, 2021), or detection limitations due to mesh sizes (Arthur *et al.,* 2009; Chubarenko *et al.,* 2018), adaptation of size boundaries from previous studies, or application of more advanced technology to detect plastics (Materić *et al.,* 2022). Consequently, more than 15 different size classification schemes have been proposed and established over the past two decades, and size definitions remain ambiguous and conflicting (e.g., Hartmann *et al.,* 2019; Provencher *et al.,* 2020).

Plastic shape classification

Plastic shape is a substantial consideration because shapes of different dimensions behave differently in different settings (Francalanci *et al.,* 2021). However, shapes are often very complex, and a universal shape description scheme is yet to grasp the full spectrum of shape diversity. Shapes of plastic items may be generalized into their dominant dimensions, i.e., quasi – one-, two-, and three-dimensional shapes, which respectively describe fibers, flakes, and spheres (Chubarenko *et al.,* 2016). Many of the plastic items encountered in the environment – in particular macroplastics – may be identified as distinct goods, and therefore their shape is typically described as such (e.g., bottle), rather than on the basis of their geometrical shape (e.g. OSPAR Commission 2010; van Emmerick *et al.,* 2020; Hapich *et al.,* 2022). Microplastics are typically described as fragments, granules, pellets or nurdles, spheres or spherules, beads, foams, filaments, fibers, films, and flakes (Hidalgo-Ruz *et al.,* 2012; European Commission, 2013; Zhang *et al.,* 2017; Chubarenko *et al.,* 2018; Hartmann *et al.,* 2019; Rochman *et al.,* 2019). Additionally, these shapes may have more specific descriptors, e.g., round, subround, angular, subangular, twisted, or curled; and pellets may be cylindrical, disks, flat, ovoid, or spheroids (Hidalgo-Ruz *et al.,* 2012; Rochman *et al.,* 2019). Lastly, the plastic may also be described as irregular, elongated, degraded, rough, and with broken edges (Hidalgo-Ruz *et al.,* 2012). However, many of these shape descriptors are used interchangeably and their definition is ambiguous and subjective (Hartmann *et al.,* 2019).

Motion and transport of plastic items

Plastic transport dynamics has been extensively modeled, theorized, and reviewed (Chubarenko & Stepanova, 2017; Chubarenko *et al.,* 2018; Enders *et al.,* 2019; Hoellein *et al.,* 2019; Khatmullina & Chubarenko, 2019; Lechthaler *et al.,* 2020; Waldschläger *et al.,* 2022; Ballent *et al.,* 2012, 2013; Chubarenko *et al.,* 2016; Horton & Dixon, 2018). Settling and rising velocities of different plastic polymers and shapes have been extensively studied in laboratory-based experiments, such as flume tank experiments, with results being compared against existing computational model predictions (Kowalski *et al.,* 2016; Khatmullina & Isachenko, 2017; Van Melkebeke *et al.,* 2020; De Leo *et al.,* 2021; Zhang & Choi, 2021; Francalanci *et al.,* 2021; Khatmullina & Chubarenko, 2021; Choi *et al.,* 2022; Kuizenga *et al.,* 2022; Mendrik *et al.,* 2023; Lofty *et al.,* 2023; 2024). However, due to classification challenges and computational power, parameters used in modelling (van Sebille *et al.,* 2015, 2020; Díez-Minguito *et al.,* 2020), are often simplified, such that the findings may have a limited application. Whilst settling equations are found to work well for simple shapes such as spheres and cylinders, they are less accurate regarding shapes such as fibers or films (Khatmullina & Isachenko, 2017; Mendrik *et al.,* 2023), especially where secondary motions (Khatmullina & Chubarenko, 2019; Zhang & Choi, 2021) and biofouling occur (Van Melkebeke *et al.,* 2020; Waldschläger *et al.,* 2020; Mendrik *et al.,* 2023). Additional coefficients and refined equations enhance the accuracy of the settling and rising equations considering their increased complexities. Flume tank experiments are used to study plastics under different flow conditions, such as initiation of motion experiments, to how the plastics interact with sediment (Alsina *et al.,* 2020; Pohl *et al.,* 2020; Bell *et al.,* 2021; Russell *et al.,* 2023). Microplastic behaviors for simple shapes are found to align with the Shields (1936) diagram (Göral *et al.,* 2023). Interaction of plastics with natural sediment finds that fibers are more prone to deposition than expected, likely due to their collisions and interactions with settling sand grains (Pohl *et al.,* 2020). Additionally, interaction of plastics with sandy bedforms significantly influences their formation and progradation (Russell *et al.,* 2023).

The behavior of plastic may vary depending on characteristics such as its particle size, shape, density, and other properties. The complex and often unpredictable transport and deposition dynamics of plastics are primarily attributed to the varying influences of these key characteristics. For example: i) shape seems to affect the settling of a particle more than small variations in size (Khatmullina & Isachenko, 2017; Mendrik *et al.,* 2023); ii) if a plastic particle floats, its size and density does not meaningfully influence the rate at which wave action will aid it drifting to shore (Alsina *et al.,* 2020); iii) fibers may be entrained and deposited at markedly different thresholds than expected due to their shape, orientation, and deformability (Pohl *et al.,* 2020); and iv) elongated shapes have a different impact than spheres on erosion from bedforms (Russell *et al.,* 2023). Additionally, films and fibers present further uncertainty as they can change their shape whilst settling (Zhang & Choi, 2021; Choi *et al.,* 2022), which calls for models that include probabilistic dependencies (Khatmullina & Chubarenko, 2019), or machine learning algorithms (Goldstein & Coco, 2014), such that we can forecast accumulations (Shamshirband *et al.,* 2019). Therefore, it is critical to understand the full spectrum of characteristics that a plastic particle or item exhibits, which may be accomplished through accepting plastic as a sediment.

Plastic as a Sediment

In accepting plastic as a sediment, we can meaningfully integrate the fundamental strengths of sedimentology into how we observe and understand plastic through i) objective observation before classification and interpretation; ii) recognition of spatial and temporal changes; and iii) developing an adaptable and flexible framework. Existing schemes for assessing the physical parameters of plastic are not appropriate to simply merge and adapt because many require discipline- or region-specific knowledge and understanding (Van Emmerik *et al.,* 2020; Bermúdez & Swarzenski, 2021). The central challenge in building a connective and consistent understanding of plastic particles using the existing principles of sedimentology is centered around the inherent variability of properties that plastic exhibits, which are beyond the standard sedimentological classifications. These variabilities mean that the behavior of plastic does not generally scale with particle size, and in sedimentology, sediment grain shape is typically considered as simple and scale independent. As such, we must extend the existing methods using the core underpinning philosophies from sedimentology to develop a flexible and simple solution.

Objective Observation before Classification and Interpretation

Before discussing classifications, it's crucial to understand the principles of objective observation that guide such descriptions. An objective description is consistent, repeatable, and quantified where possible, encompassing measurable characteristics such as scale, color, or mass of an object, whilst remaining free of personal bias or subjective interpretations. It is important to avoid interpretations as they may vary between scientists, as well as over time as new perspectives are developed. Therefore, distinguishing between objective observations and subjective interpretations substantially enhances the usability of the dataset.

In plastic studies, if an object is readily identifiable (e.g., bottle), this interpretive name is given, whereas if the object is *not* known (e.g., fragment), it is binned under "unidentifiable" or objectively described, typically by size and polymer type. As plastic continues to degrade in the environment over time, the "unidentifiable" category will grow, such that the descriptive approach becomes necessarily prevalent. Additionally, the delineation of whether an object is identifiable or not is biased towards regional knowledge, and the level of expertise or experience that the individual has. There is also a challenge of variability amongst categories, which is difficult to navigate using current schemes, as if an item is labelled as "bottle", it is not able to account for different scales (beyond small or large). Importantly, the composition or state of degradation, compaction, or degree of deflation of the object is not always recorded, yet each of these factors will impact how the object to behaves in the environment.

We also rely on shape descriptors such as pellets, nurdles, spheres and beads, but these names are often interchanged such that the terminologies are a mixture of subjective interpretations and descriptions (Hartmann *et al.,* 2019). It is important to not wrongfully interpret the terms pellets, nurdles, or beads as they may refer to raw pre-production plastics (e.g. nurdles), and therefore represent primary microplastics, which is a critical distinction when seeking to understand plastic in an environmental context. Microplastics that have been derived from larger fragmented items are known as secondary microplastics, but may themselves exhibit similar shapes to primary microplastics and could be mistaken for them, particularly if they have become abraded and rounded in the environment over time, (e.g., Hartmann *et al.,* 2019; Provencher *et al.,* 2020). The term "fragment" infers that the particle is a secondary microplastic and typically refers to angular particles of rigid polymers, however, some of these angular shapes are primary plastics. Additionally, there is limited continuity in usage of the term, as if a fragment of unidentifiable film is found, it is still technically a “fragment”, yet commonly classified as “film”. Therefore, it is clear that using subjective and interpretive terminologies is confusing and hampers the objective collection of plastic data and, by extension, the interpretive process.

There is also the challenge of location bias, for example the River-OSPAR protocol (OSPAR, 2010; van Emmerik & Schwarz, 2020) has 111 specific item categories, but these categories have been largely developed on studies of European rivers as they are the most frequently studied (Owens & Kamil, 2020). Therefore, if this style of classification were to be used in another location, there is a priority for European-prevalent trash to be most clearly categorized, and a challenge in translating how the categories are defined, such as the difference between a bottle and a container. As such, it is important to recognize that the term “bottle”, and other object names are subjective interpretations based on past function of the plastic particle, not an objective description of its present geometrical morphology.

Through extending the objective approach of sedimentology we can: i) study the independent variables of plastic objects, such that we can better understand which properties drive its distribution in the environment, hence aid predictive models; ii) return to primary observations if an object has been misidentified, and reconsider an alternative interpretation from base principles; and iii) develop a scheme that may be readily implemented internationally with limited interpretive barriers.

Recognition of Spatial and Temporal Changes

Sedimentology does not only attend to modern settings, but also to ancient deposits that are millions or billions of years old, both on Earth and extra-terrestrial surfaces. In these contexts, the tools and understandings developed enable past processes and paleoenvironments to be reconstructed. The core context of how this is achieved is through compiling information from static, in situ, data sets, from which spatial and temporal changes are progressively mapped, recorded, and interpreted. As such, in sedimentology, we do not focus on how a specific particle has responded to change, we focus on gathering information from many particles in a “snapshot” of time, to determine trends that then enable insights for interpretations and predictions.

Over time in the environment, both plastic and sediment particles will become smaller, and corners and edges will become more smoothed, whilst plastic may additionally become deformed and chemically changed in the environment. The progression of change is constantly away from the form of the original object. It is a type of forensic analysis to identify what plastic fragments and particles have been degraded from, which is like how sedimentology operates. However, in the same way that we do not consider it immediately relevant that a grain of sand on a beach may once have been part of a boulder, for the purposes of classifying plastic as a sediment, the plastic particle should initially be objectively considered as its own entity, independent of its interpreted origin.

If plastic objects have been released into a beach environment over time, they will range from complete to fragmented, therefore, by studying the plastic objects present, the phases of degradation will be elucidated. From this, past processes can be understood, and predictions for the future degradation can be made, hence invoking a temporal understanding that has been inferred with a series of objective and static snapshots. Through repeating this exercise over time, the inferences can be tested and refined, thereby building and refining a predictive framework.

Additionally, it is important to note our impacts on the spatial and temporal changes that we make in studying and mobilizing plastic. If materials are removed, cleaned, untangled, reshaped, organized, or emptied of air, water, and sediment, then the data that is then collected is disconnected from its in-situ environmental status, i.e., you may discern what the object is, but you lose the data to work towards understanding how it may have become deposited, which affects the potential for predicting how it was transported. For example, a bottle with a lid on that is filled with air will behave very differently to one filled with sand. Additionally, a rope that is found as a tightly wound coil should be measured in that state, as to unwind the rope and measure those dimensions would be an irrelevant statistic in determining its transport process to this position. Therefore, the environmental status of an object is very important for improving our contextual understanding.

In some plastic studies, it is necessary to collect the material and then assess it later, which means manually and superficially cleaning sediment and organic debris from studied items to approximate their sampled condition (e.g., de Lange *et al.,* 2023), however, in most studies, the process of item collection and processing is not shared as part of the methodology. Nonetheless, we must endeavor to describe the state of the item as we find it, not as we have changed it. Therefore, materials ought to be recorded in situ, and their status preserved during analysis where possible. If material must be ex situ, then material should be collected with enough information to be able to reconstruct its situation, i.e., its location, orientation, and other relevant environmental context, which may include time and date, perhaps as well as the weather, status of the tide or water level if considered relevant to the setting. The amount of information recorded ought to concur with the objectives of the study and be sufficiently detailed, such that if there are spatial trends, or environment-related patterns, the data is detailed enough with sufficient isolated variables, that any patterns may be meaningfully discerned.

The Significance of an Adaptable and Flexible Framework

Sediment is described within a framework that is consistent, adaptable, and flexible to suit specific research questions. However, there is an important central set of classifications and methodologies whose standardization allows for different studies to be compared, e.g., grainsize, composition, and grain shape. Therefore, the simple framework can support complex studies as all the sedimentological data has a common and comparable root, so it is readily feasible to inter-relate multiple studies. For example, if a study required investigating grain surface scratches, this data set would be collected along with basic sediment attributes such as grainsize, such that the study may be made immediately relevant within the global knowledge and understanding of sedimentology. In plastic studies, we presently have no comparably consistent approach and a multitude of unknown unknowns. By adopting the strengths of sedimentology in having a consistent approach to basic attributes with common classification principles that may be flexibly added to, we can build an appropriate solution to a critical and growing challenge.

A Universal Classification Scheme for Plastic

The classification scheme has been developed from existing approaches for the study of sediment and plastic and includes novel approaches where existing methods are insufficient. The methodology provides a core framework, equivalent to that which exists in sedimentology, whilst also maintaining flexibility for specialist studies. As such, the classification scheme will aid in connecting the physical characteristics of plastic to their transport processes, spatial accumulation tendencies, and temporal changes, thereby enabling deeper understandings and improved inter-relatability of studies. It is important that the core framework of this classification scheme is shared with sedimentology as it will allow for the development of comparison between sediment and plastic particles, thereby deepen our comparative understanding of sediment and plastic, which will further aid in predicting plastic behavior and distribution in the environment.

The focus of the classification scheme is based on the characteristics that are known to drive sediment (hence also plastic) behavior in the environment, which are size, shape, absolute density, and mechanical properties. The classification scheme is designed to encompass any object of any properties and may even be applied beyond plastic. The order in which the classification is presented corresponds to the order in which these components ought to be assessed. First, the morphological analysis of the particles (size and shape) is discerned, as these analyses focus on the external presentation of the object, then secondarily the potentially more invasive, even sometimes destructive, analysis of the absolute density and material properties is undertaken. None of the characteristics (size, shape, absolute density, and mechanical properties) are intended to be observed in isolation; all elements ought to be considered to allow for a full description of plastic items of various scales. It has been demonstrated that some plastic characteristics are more important than others in determining their environmental behaviors, but these relative importances change between settings. Therefore, all characteristics of an item should be assessed in every case, to enable cross-environmental usage and applicability of the datasets. We do not yet know how every element of the following classification will relate to plastic behavior in the environment as not enough data has been collected in this context of assessing plastic as a sediment, so future substantial advances will inform the procedure. To aid with this necessary completeness, a summary sheet of the methodology and a log sheet for recording observations may both be found in the supplementary material (Supp. 1 and 2).

Unifying Size Classification for Plastic

Despite the robust size classification scheme for sediment (Fig. 1), it would not be appropriate to directly relate it to plastic because it would be too discordant with prior studies to be of practical and integrative use, and it would not divide plastic into categories that are themselves useful for further understanding. The different properties (e.g., polymer types) of plastic objects are so variable that size alone cannot carry the same priority in plastic studies as it does in sedimentology. As such an objective and practical meaning for classifying plastic sizes needs to be found in a different way.

It is recognized that, like all natural materials, plastic size is a continuum (Kooi & Koelmans, 2019), however, plastic is most typically defined into size divisions of nano, micro, meso, macro, and mega, of which there are no settled definitions (e.g., Hartmann *et al.,* 2019). Smaller plastic scales have been most heavily disputed as there is a large body of work in micro- and nano plastics due to the immediate ecotoxicological concerns. Whilst the scale of sizes is of course a continuum, the nomenclature needs to be consistent and meaningful, as was argued for sedimentology by Wentworth in 1922.

In sedimentology, there was a lengthy study conducted by Chester Wentworth (1922), where he surveyed sedimentologists through writing letters to understand the terminologies and size classification boundaries they were using. Upon receiving responses from "about thirty of the men," he developed a proposed scheme and sent it to "about a dozen" sedimentologists in the US and England for feedback. The final decisions for unification were then published by Wentworth (1922). In this similar enquiry regarding plastic size classifications about 100 years later, the internet enables a broader set of perspectives to be drawn upon through accumulating information via manuscripts and conversations both in person and online. Many reviews have been assembled considering plastic in the environment (e.g. Hartmann *et al.,* 2019; Waldschläger *et al.,* 2022), such that this study does not begin at the same state of origin that Wentworth experienced. The scheme below has been available as a preprint for comment for more than a year, presented to experts in the field at international conferences for more than two years, as well as undertaken the peer review process. Therefore, whilst it is interesting and useful to note the historical development of sedimentological classifications, it is neither realistic nor practical to follow this template in today's context of modern connectivity. As such, in the context of describing plastic size, we clarify that the below scheme has been derived from considering a broad context of applications and discussions, with each delineation being carefully deliberated regarding its objective and practical relevance to how we can best consider plastic as a sediment (Fig. 5).

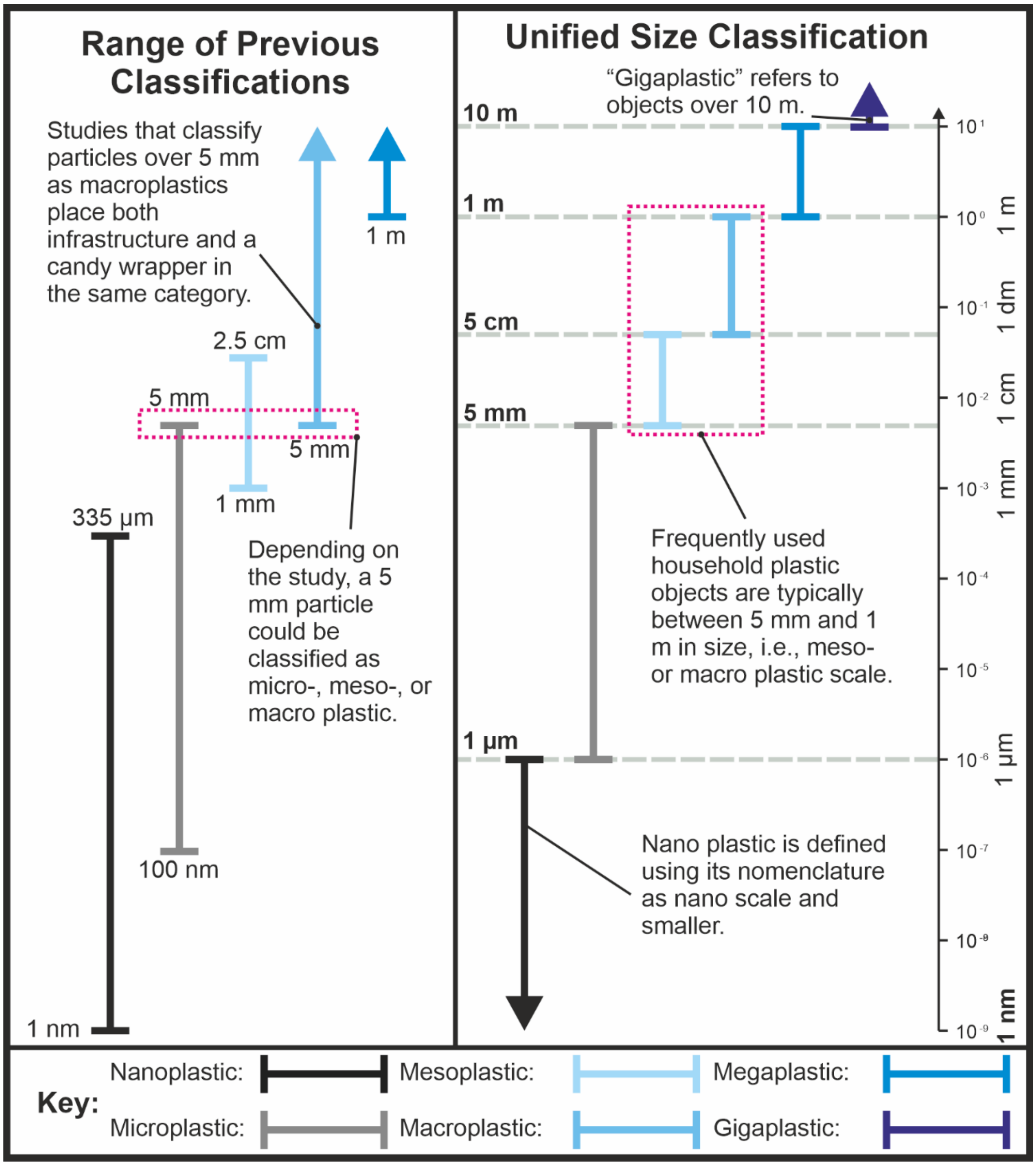


Figure 5 – The combined range of upper and lower boundaries gathered from previous classification schemes, demonstrating a wide range. In the present range of classifications, the same particle could be justified as micro-, meso-, or macroplastic, therefore, the unified and justified revision on the right offers the opportunity to return quantified meaning to these terms. Boundaries from: (Arthur *et al.,* 2009; Barnes *et al.,* 2009; Stamm, 2011; Desforges *et al.,* 2014; Andrady, 2015; GESAMP, 2015; Koelmans *et al.,* 2017; Hartmann *et al.,* 2019).

Nanoplastic (≤1 nm - 1 µm)

The minimum size for nanoplastic is generally considered to be smaller than or equal to 1nm, as any particles smaller than this are typically broken down into their constituent atoms. The definition for nanoplastic is determined practically by the nomenclature, therefore from 1nm to 1000nm (1μm), which aligns with Browne *et al.,* (2007), Andrady, (2015), GESAMP, (2015).

Microplastic (1 μm – 5 mm)

Microplastics are the most intensely studied of all the size classifications. If the boundary was justified according to its nomenclature prefix "micro" it would be defined as between 1 micron – 1000 microns (i.e. 1 millimeter). However, the boundary definitions are appropriately functional, in that the upper boundary for the size of microplastic is 5 mm (Andrady, 2015), as it is an upper particle size that is commonly ingested by many marine animals and has the potential to cause harm to them and the rest of the food chain (Arthur *et al.,* 2009). The upper boundary for microplastic has been widely accepted as 5 mm since the NOAA meeting (Arthur *et al.,* 2009) and is therefore impractical to move. As such, the size boundary from microplastics is from 1 μm to 5 mm.

Mesoplastic (5 mm – 5 cm)

Mesoplastics are between 5 mm and 5 cm and denote a size category that represents a functionally distinctive category of pocket-sized, thereby exceedingly portable and often disposable and single-use, plastic items. Many items commonly found in an urban environment such as cigarette butts, sweet wrappers, hair elastics, and much more, are casually and readily transported where people travel. Additionally, items in this size bracket would fit through drain covers, therefore mesoplastics and smaller represent the most likely size bracket to route to waterbodies via road drains. As such, we anticipate incidence of items this size on streets, in drains, and in street-side refuse bins.

Macroplastic (5 cm – 1 m)

Macroplastic is commonly the uppermost size consideration attributed to plastic items, but it seems grossly insufficient to consider everything from a bottle to a caravan exterior in the same category because they will behave remarkably differently in the environment and accumulate under different physical principles. We most frequently interact with plastic items smaller than 1 m in size, which is reflected by the typical depth of a household refuse bin. Notably, the presence of and size of a household waste bin reflects the experience of residents of countries with a higher GDP, however plastic items are often generated with such consumers in mind, so the size category and functionality of plastic items this size is similar between locations. The upper limit for macroplastics has been placed at 1 m, which aligns with GESAMP (2015), and Andrady (2015).

Megaplastic (1 m – 10 m)

Megaplastic recognizes the boundary at which plastic waste is more likely to be taken to a specialist refuse site, rather than disposed of through household waste collection. As such, they may be referred to a landfill site, recycling facility, or to specialists for dismantling composite components. The upper limitation here is 10 m, as this is the boundary at which plastic items are larger than what would be commonly used in the household sector and are more likely found in the commercial sector. Due to the differences in management of this scale of waste, the way that plastic of this scale accumulates will differ from the other size categories.

Gigaplastic (≥ 10 m)

The term gigaplastic is newly introduced in this study to describe plastic items that are larger than 10 m in size. They are differentiated from megaplastic because the larger size indicates a larger-scale process or event. As this is a new terminology, we are unable to present a quantitative basis as the data has not been collected yet, however we know of enormous rafts of large-scale materials that are mobilized to the ocean after catastrophic events such as floods and tsunamis, so assessing this scale of item could be an important indicator of these event deposits. Additionally, objects of this scale may be highly specialized and managed and manufactured in set facilities from production to its decommissioning, such as fishing and commercial transport, within which some polymer types and chemical pollutants may be more prevalent. Lastly, the scale of disruption that would occur if a 10 m scale item was in a river would be more immediately important to locals than a 1 m item, as a 10 m + item may block a river causing local neighborhoods to flood. Additionally, a net that is 1 m in scale will be a threat to a different population of ocean creatures, whereas a large-scale 10 m + net can kill a whale. These examples demonstrate that the larger-scale category is sufficiently different in its source, transport, and deposition to be considered separately.

Novel shape classification scheme for plastic litter

There is a wide variety of complex classifications and descriptors, which may be appropriate for specific studies, but for this basic framework we have refined it to a simple overarching shape describing dimensions, and holes, that seeks to enable simplification of complex objects into base principles that will aid the inter-relatability of studies. It is important to assess the shape of a particle because it affects its motion, properties, and behavior (Stückrath *et al.,* 2006).

Dimensions

There are many morphological descriptors such as fiber, cube, and tube, however, for the purposes of a uniform, consistent and quantifiable comparison with sediment, we use the Zingg (1935) objective dimensional categories. If the long axis (ℓ), short axis (s), and interim axis (i), are measured, then the elongation (i/ℓ) and flatness (s/i) ratios may be calculated. The ratios for elongation and flatness will determine if the shape is dimensionally a sphere, rod, blade, or disc (Fig. 3). As this approach uses dimensional ratios, it is scale independent and can be readily plotted on a graph for easy and practical quantification. Therefore, this framework aligns with and advances on approaches in plastic studies that outline quasi-one, -two, and -three dimensional particles (Chubarenko *et al.,* 2016; Francalanci *et al.,* 2021). For more complex shapes, we can consistently approximate by determining the total average shape as relates to the dominant portion of the object. If uncertainty is due to shape complexity, such as protruding elements, or cavities, then this decision ought to be executed via considering the total average shape it occupies, e.g., a plastic coat hanger is a blade.

Texture and Roundness

Among the complexities of plastic particles and objects, the roundness of a plastic particle does not necessarily correlate with the density of a surface texture, as depicted by Powers (1953) (Fig. 4). The intensity of the texture refers to its cross-sectional relief, which may have been originally manufactured or a product of environmental abrasion. To address this, we have developed a scheme that enables the independent classification of surface texture density, intensity, and shape (or corner) roundness (Fig. 6). Density is depicted as irregular but may also be regular, while roundness newly includes the depiction of a corner as well as a grain, making it more readily applicable to more scales and a greater range of shapes.

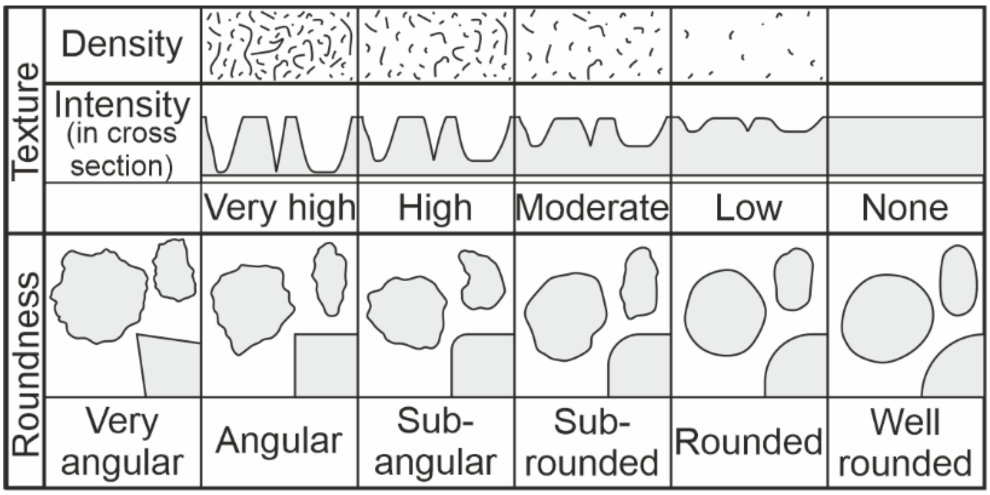


Figure 6 – Demonstrates the classification for the independent assessment of surface texture density, intensity, and shape (or corner) roundness.

Holes

The other component of shape that we assess to classify the character of a plastic particle is the existence and nature of holes. We searched for a methodology that would allow for a simplification of complex objects such that they can be objectively described. Even for simple shapes, identifying the number of holes can be a challenge without a methodology. For example, a straw has one hole, the same as a doughnut, but a straw is frequently argued to have two holes. As such, the established mathematical study of topological homeomorphism significantly aids here in allowing for a consistent set of principles to be applied to objectively define the number of holes in a three-dimensional shape. Topology is the mathematical study of the properties of geometric objects that are preserved under deformation; a homeomorphism is the mapping and preservation of topological space under topological deformation, i.e., a continuous function between topological spaces with a continuous inverse function. Through applying topological homeomorphism to the shape of a straw, the morphology collapses into a torus and therefore clearly has one through hole. As such, for assessing the holes in a shape, here we take inspiration from this mathematical concept as it enables objective and consistent description of shapes (Fig. 7).

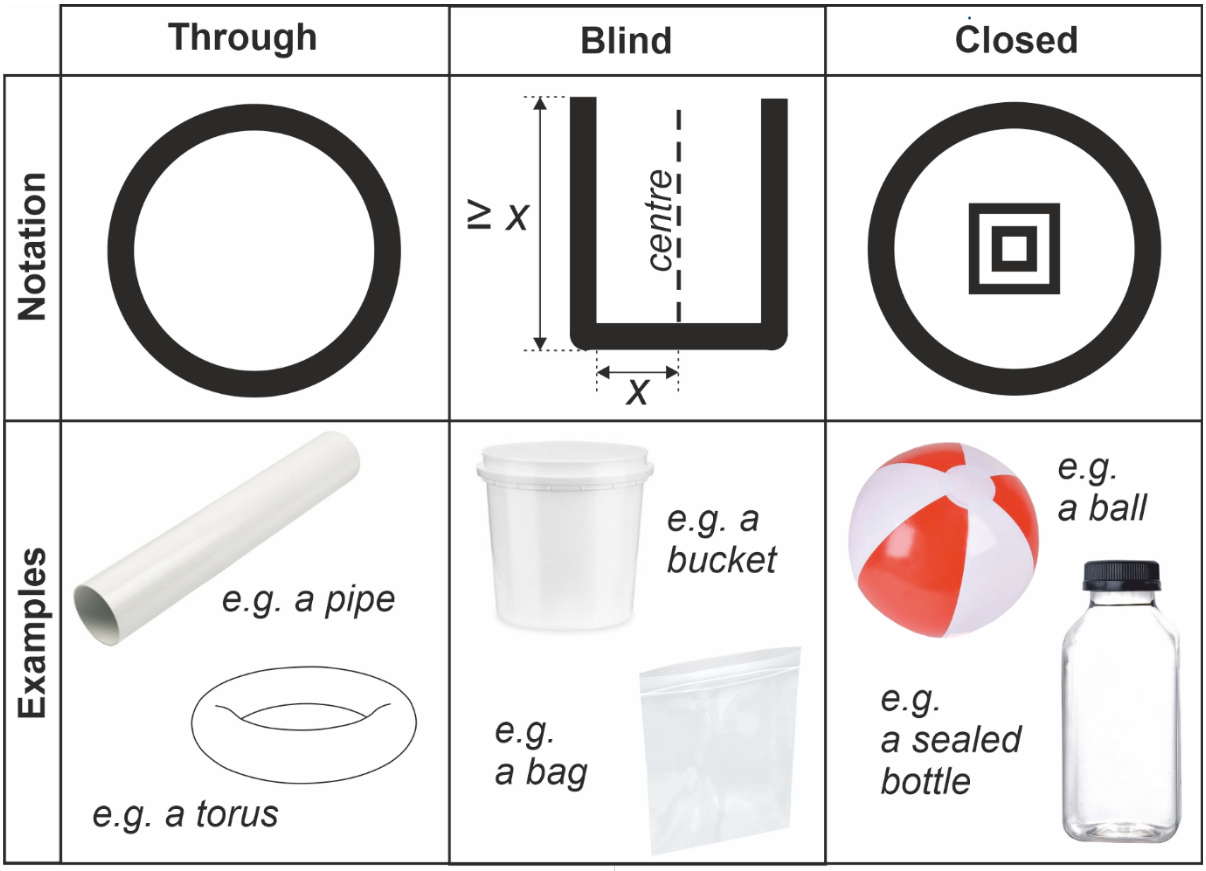


Figure 7 – Demonstrates simple hole examples. Note that in blind hole, x represents half of the internal width of the container. If the blind hole was not round, x would be half of the internal width of the container at the narrowest point.

Each type of hole contributes to the understanding of how an item will be transported, and perhaps how it will interact with the environment on its journey, i.e., how it may generate microplastics due to abrasion and fragmentation, and how and where it will accumulate.

- **Through holes** are important as water and materials may flow through them, so they can create internal depositional and biological environmental conditions that differ from the wider environment. Through holes pierce an entire object, such as a hole through a pipe or a doughnut and may be objectively defined using topological homeomorphism.
- **Blind holes** are important as they can create protected environments in which sedimentation can occur, and internal surfaces are less likely to become abraded. Blind holes are cavities where the hole is a depression in the object, such as the hole that defines a bucket. In this framework, we quantifiably define a blind hole as a hollow whose minimum depth is greater than half of the width of the hole, as measured at the narrowest point on the inside of the hole. A hole with an opening diameter smaller than its average width is always called a blind hole, regardless of how deep it is internally.
- **Closed holes** are important as they are a concealed environment and if they trap air, water, or sediment, they may markedly affect the absolute density and thus buoyancy and behavior of the object. We define closed holes as one that material will not readily move into or out of.

If we consider the surface of a sphere of plasticine, any way that it can be molded without breaking that surface is considered homeomorphic with that sphere. To break the surface would be to break the plasticine into pieces, break the surface to form a through hole, or join parts together to form a through hole. As such, the shapes of a soccer ball, bucket, an open chip packet, or a dinner plate are homeomorphic to a sphere, as they can be molded from one shape to another without breaking the surface. Within these examples, a dinner plate has no holes, a soccer ball has a closed hole, and the bucket and open chip (or crisp) packet each have a blind hole, though none have through holes because if they did, they would not be homeomorphic with the sphere.

A through hole disrupts the topological space of a sphere, i.e., it breaks the surface of the plasticine, thereby defining a new principal shape as exhibited in Figure 8 by a doughnut, or torus. The doughnut on the right of Figure 8 is homeomorphic with a pipe, a funnel, or a straw, as each has one through hole and so can be molded from one to another without disrupting the topological functions.

A more complex shape, such as a mug, is still homeomorphic with the torus, as both have one through hole and the blind hole, where you would put your coffee, can be removed through topological deformation without breaking the surface. Figure 8 shows the famous sequence in homeomorphic topology whereby a mug is homeomorphic with a doughnut.

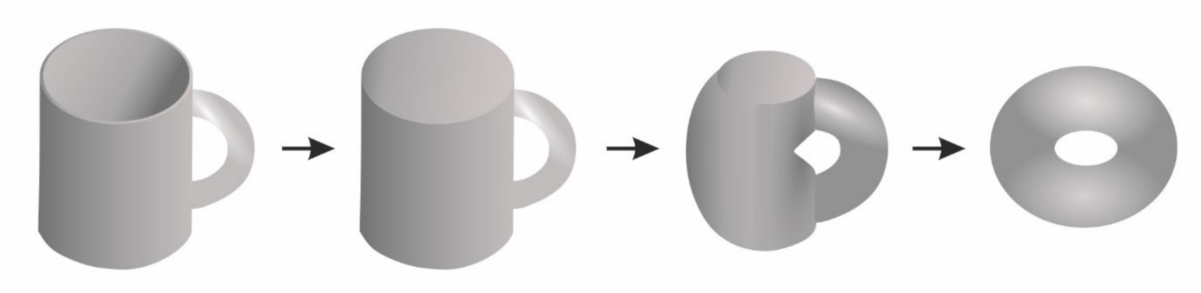


Figure 8 – A famous topological shape is how the mug can morph into a doughnut, i.e., a torus. The blind hole in the mug may be filled in and as the mug becomes its most simple topological form, the torus results.

It is through describing the number of each type of hole that we can record key characteristics of a plastic particle. The methodology of recording holes is scale-independent and can apply to any level of complexity through the notation: TnBnCn (Fig. 9).

There are three additions to the notations that aid clarity of observation:

1. Where the shape becomes more complex, it is key to identify a threshold at which further detail will not aid the description. As a framework baseline, we suggest a maximum of 10 of each type of hole. For example, if the plastic particle demonstrates more than 10 examples of a hole type in an item, notate as 10+, e.g., plastic bubble wrap packaging would be notated T0B0C10+. For complex objects, such as a 3D printed model where there are more than ten through holes, blind holes, and closed holes, it would be notated as T10+B10+C10+. For the purpose of describing the object, to later understand its environmental behavior, from this notation we can determine that it is a complex and porous object, which is significant.
2. If the item is made of a polymer that is opaque, but at least one closed hole is suspected, a question mark (i.e., “?”) is used to precede the minimum hole value and show that it is an interpretation. For example, the ocean buoy in Figure 9B is made of

an opaque yellow polymer and therefore it is not possible to constrain if one or more closed holes are present, yet it is suspected, so it is notated T1B0C?1+.

3. Additionally, we must consider textures that are themselves composed of through holes, such as a net, fabric, or rope, as they have the capacity to hold water and other material and change its function as a result of its porous properties, as well as shed microfibres. Whilst a simple net may be notated as T10+B0C0, challenges arise when considering a fishing net that is shaped into a blind hole, as the net itself is composed of through holes, thereby invalidating the existence of a blind hole. It is not appropriate to rely on scale dependency for hole categorization as it is limited when applied to the range of mesh sizes, so instead we use a notation for texture: i) where the material is composed of more hole than solid is notated as "net", so is notated as TnetB0C0; or ii) where the material is composed of more solid than hole, it is porous and notated as "por" for porous, so a towel is notated as TporB0C0. As such, the fishing net that is shaped into a blind hole is notated TnetB1C0.

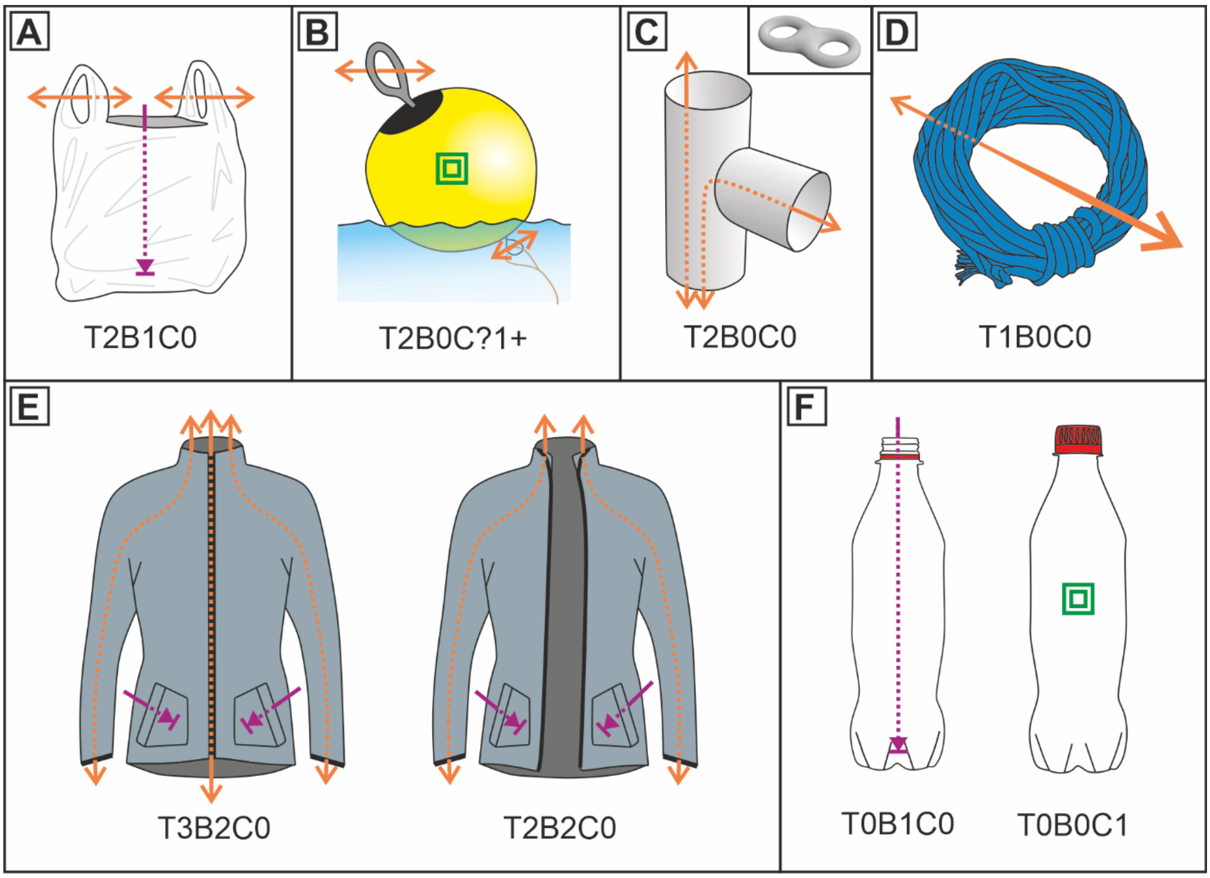


Figure 9 – Examples of the concept and application of the hole descriptor methodology. Purple arrows represent blind holes, orange arrows are through holes, and green symbols are closed holes. A) A plastic bag where the handles are through holes and the bag itself is a blind hole; B) an ocean buoy where there is opaque plastic and at least one closed hole assumed, and two through holes; C) a pipe junction with two through holes, as its homeomorphic alternative is a double torus as shown in the insert; D) a coil of rope with one

through hole; E) a jacket with two pockets both zipped up and unzipped, where the zipped jacket has an additional through hole than the unzipped jacked; F) a bottle with no lid on exhibiting a blind hole, and a bottle with a lid on exhibiting a closed hole.

Whilst it is important to record all the holes in an object, some will be more important than others in defining the shape and function of the object in the environment, e.g., a pipe with a small hole drilled into it would notate as T2B0C0, but the small hole may not be of importance to the sedimentary dynamics. As such, a complementary and *interpretive* note of hole significance is made with the goal of minimizing consideration of incidental holes that do not contribute to understanding the overall shape of the object. Although subjective and interpretive, this additional note helps to reflect the dominant characteristics of the objects, which may offer further insights during analysis.

Absolute Density and Polymer Type

The absolute density (Ad) (also often referred to as net density or effective density) is an important parameter because it controls the buoyancy of a particle. In fresh water, positively buoyant items (Ad < water density) will float on the water surface while negatively buoyant (Ad > water density) items will settle though the water column, eventually reaching the sediment bed or seafloor. Neutrally buoyant items (Ad -1 ~ water density) have an absolute density equivalent to that of water and will suspend within the water column. Additionally, the Ad value ought to be considered in relation to the size of the particle, such that the submerged specific gravity (R) may be calculated and multiplied with the diameter (D) to find the RD value of the particle (Russell *et al.,* 2023). The RD value is important because two items may be of the same density, but different sizes, therefore may behave differently in the environment.

In sedimentology, the absolute density of a sediment grain typically directly relates to its mineralogy or composition e.g., the density of quartz is 2.65 g/cm^3, which is the typical density of quartz-rich sand grains. However, pumice, a naturally occurring volcanic rock has a similar density (2.65 g/cm^3 - 3.3 g/cm^3), yet can float on water. Pumice is porous, such that its environmental behavior is determined by its absolute density rather than the molecular density of the rock itself. Plastic that combines with natural components such as water, sediment, and air, may have an affected Ad value, which alters how it will become transported and deposited in the environment. As such, whilst we may know the polymer density of a bottle, in an environmental context, it is perhaps more important to know if the lid of the bottle is on or off, and the properties of materials that are enclosed in holes. Figure 10A shows how a bottle with a lid on, hence exhibiting a closed hole, the content of which significantly affects the absolute density of the object and therefore its environmental status. Additionally, the closed nature of the hole means that this property may persist for some time. In Figure 10B, we see the closed holes are now blind holes as the lids are off for each bottle depicted. As these bottles move through the environment, they may temporally change their Ad value and become more affected by their surroundings. Bottles or cups with no lid have been found to be associated with the water level, potentially due to their increasing mass resulting from taking on water (Roebroek *et al.,* 2021).

As well as content, the material properties of a particle in the environment may change over time due to effects of weathering, chemical leaching (Persson *et al.,* 2022), and growth of biofilms (Galloway *et al.,* 2017; Burns & Boxall, 2018; Mendrik *et al.,* 2023) that change the Ad of the particle or object over time. As such, plastic objects and particles may have affected transport mechanisms for reasons that extend beyond their polymer density. Therefore, it is significant to record these observations as the status of the object or particle holds critical context for understanding plastic particle transport and accumulation in the sedimentary environment.

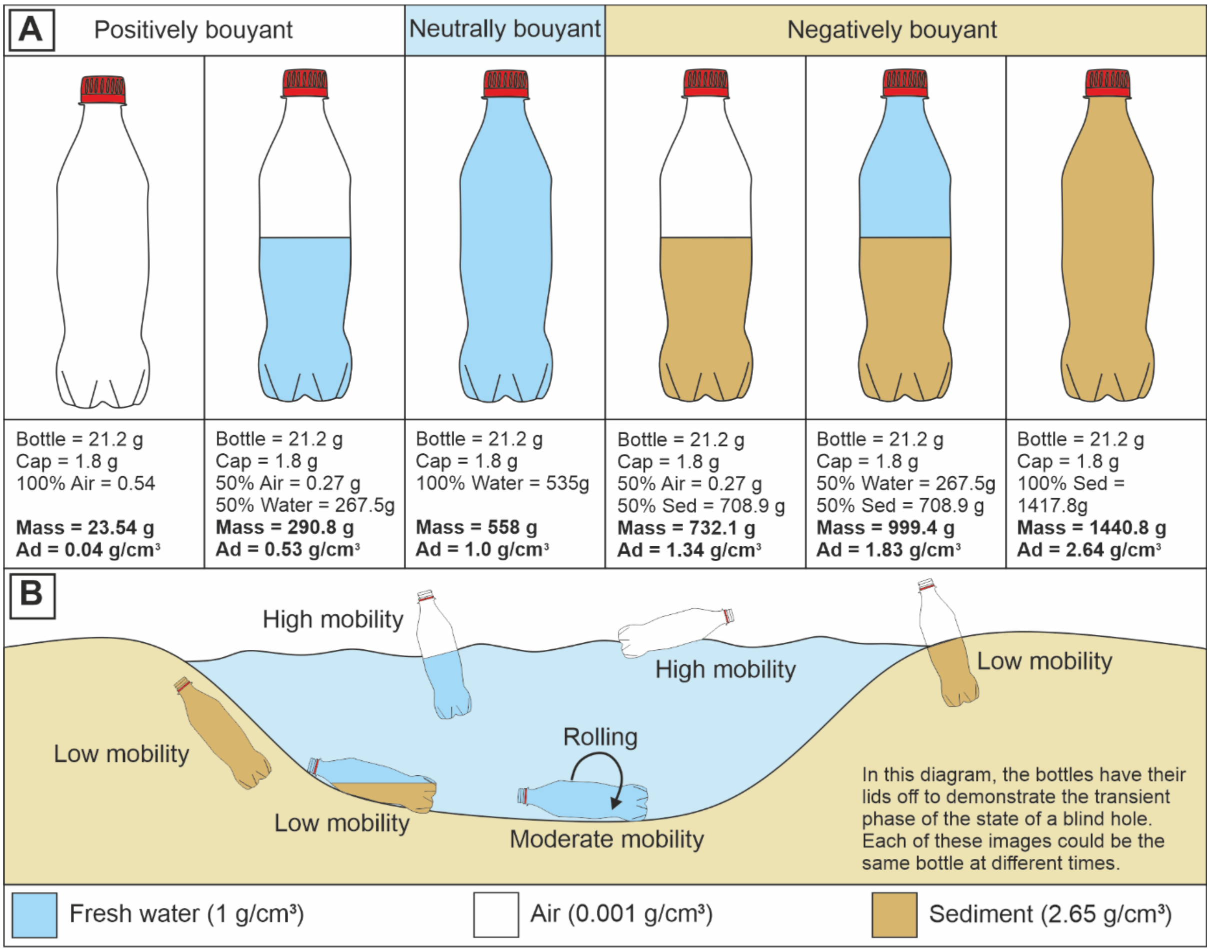


Figure 10 – A) A demonstration of the importance of using Absolute Density (Ad) over polymer density. The bottles represented in the figure are 500 cm^3, made of polyethylene terephthalate (1.38 g/cm^3), and the bottle lids of polypropylene (0.92 g/cm^3). The bottle can hold up to 535 cm^3 (internal volume – used to calculate bottle content) and displaces 545 cm^3 of water (external volume – used to calculate Ad). B) The impact and importance of different Ad values in the environment.

Many commonly produced plastics (50-60% of all produced) are less dense than water, so float on water (Lebreton *et al.,* 2019), and some plastic types are the most resiliently buoyant particles in the natural environment and may be hydrophobic. The transience of the floating phase of plastic materials prior to their eventual burial is longer than for most natural particles. Floating plastic particles flow at the water surface (i.e., the air – water boundary), so are mobilized and transported by different processes than natural sediments as they interact with different components of the system (Roebroek *et al.,* 2021). Floating materials are more likely to be moved by wind, even mobilized into the atmosphere, and it is more likely to be caught in tree branches, than material that travels in the water column or interacts with the riverbed (Vriend *et al.,* 2020). Importantly there is also a bias in that floating plastic items are more likely to be collected and recorded in environmental clean-up operations as they are more visible and safely accessible than materials under the water's surface.

To describe the floating material, we recommend the term "floating load" as used by Stubbins *et al.,* (2021), as it is a term that is concordant with the other sedimentological terms of "bedload" and "suspended load". "Floating" is already a common descriptor for a range of materials in environmental studies, such as "floating pumice raft" (e.g., Manville *et al.,* 2002), for plastic studies, "floating plastic" (e.g., van Sebille *et al.,* 2015), and for vegetation studies "floating vegetation" (e.g., Schreyers *et al.,* 2021), and additional variations therein such as "floating debris" (e.g., Lebreton *et al.,* 2019). The term "load" is broad, such that it encapsulates natural and human-made materials and infers the motion of transport in the combined moved mass of "load", i.e., we describe "bedload" in motion, and "bedload particle" properties. Uniformly framing the floating load as an integral sedimentary component is a minor, yet important adjustment of the existing frameworks that will have important repercussions in unifying our understanding of what forces act upon the transport of plastic as a sediment (Fig. 11). In this context, floating load includes the surface microlayer of plastic particles (Stubbins *et al.,* 2021), as it is still functionally part of the floating load.

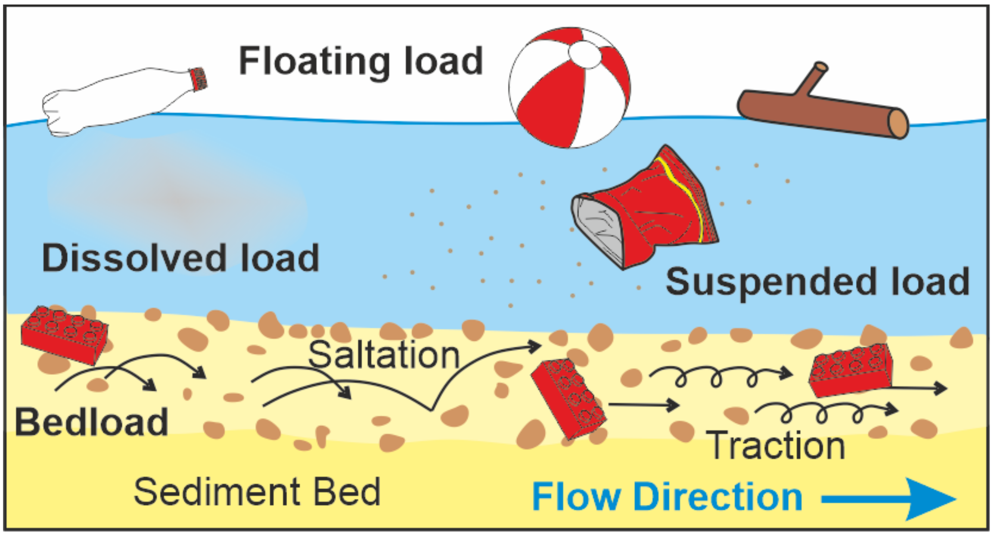


Figure 11 – A figure to show the variation of transport of natural sediment in open channel flow (e.g. rivers)

Chemical, electrical, and mechanical properties

Plastics have a great range of variability in their chemical, electrical, and mechanical properties, which are constantly changing in the environment (Galloway *et al.,* 2017) and affect its durability (Thompson, 2006). As well as mechanical fragmentation, plastic particles can photo- or thermo-oxidise, undergo hydrolysis, and biodegrade (Gewert *et al.,* 2015; Dimassi *et al.,* 2022). For example, molecular changes to the polymer type and leaching additives, may lead to increased brittleness, thereby exacerbating its ability to fragment into microplastics (Song *et al.,* 2017), such as a flexible polymer may become more brittle through exposure to humidity or UV light (Lopez *et al.,* 2006). Rates of change and fragmentation of plastic depends on the polymer and its morphology and degradation grade, but this remains poorly investigated outside laboratory conditions (Gewert *et al.,* 2015). Therefore, whilst the polymer type can be helpful to know, it does not reliably solve the objective description of the properties of a plastic particle in its present condition. As such, whilst plastics are a new category of sediment, the mechanisms by which sedimentology works are clearly insufficient to manage description and understanding of plastic behaviors, as we have outlined through this manuscript. However, by describing key properties, we can add to our descriptions and knowledge of the distribution of, and relative importance of, plastics with certain properties across the environment.

To record plastic properties, and therein the transformation of durability of plastic polymers, we here propose to assess individual characteristics of plastic particles. Such insights will enable better modelling of particles and help us to understand how plastic behaves as a sediment particle. This section is a preliminary review of the range of behaviors that we need more specific studies on, and explanations of how those properties may impact the potential behavior and disintegration of plastic in the environment.

Property	**Description**	**Importance**
Color	Dominant color of the plastic item or particle	Variation in temperature due to differences in light absorption may vary degradation and fragmentation rates. Certain color might attract specific organisms that mistake plastic items for food potentially influencing the transportation and deposition history of the plastic particle (Ryan, 2016).
Opacity	No light can penetrate the item through the polymer itself. Holes and porosity are not included here.	Although UV protection may be on some transparent items (Sackey *et al.,* 2015), opacity versus translucency can signal UV transparency and therefore potential influence of UV light on its degradation, so may impact the items structural longevity. Additionally, it affects the ecology that may develop inside or underneath it. Color also ought to be recorded (Martí *et al.,* 2020).
Transparency	Some to almost all light can penetrate the item, such that it does not significantly obscure the view behind the item. Translucency is included in this category.	
Brittleness	The material will break or shatter without significant deformation when under stress	Brittle plastics are stiffer and have lower impact strength, except for reinforced plastics (Rosato & Rosato, 2003). A brittle plastic in the environment may more readily disintegrate to microplastics than one that it more flexible and can deform plasticly (Tang *et al.,* 2019).
Plasticity	The material can undergo irreversible or permanent deformations without breaking or shattering	
Softness	It can be readily marked by another object	Hardness can be quantified using methods such as the Brinell hardness

Hardness	The material is more able to withstand surface indentation and scratching	testing or Mohs hardness scale, and is a characteristic of durability that is related to brittle and plastic properties (Gerberich *et al.,* 2015). A harder plastic may be more abrasion resistant than a soft one, and therefore be more resistant to fragmenting into microplastics
Flexibility	A material that can be bent or stretched repeatedly without breaking in response to an applied force	Materials with these properties can become more brittle and less flexible or elastic under high humidity and UV light exposure (Lopez *et al.,* 2006; Dimassi *et al.,* 2022), so may readily degrade to microplastics, but it is a more temporally complex response, therefore important to record.
Elasticity	Where a material can return to its original size and shape after being deformed by an applied force	
Static electricity	Electric charges within or on the surface of a material may affect its tendency to attach to other materials.	Attachment to other particles, such as plastic, minerals, and water, affects its ability to float or sink. Where plastics are charged, they may flocculate with themselves or clay minerals (Besseling *et al.,* 2017; Andersen *et al.,* 2021). Where a plastic is hydrophobic, it strongly affects its ability to biodegrade (Dimassi *et al.,* 2022) and may enhance surface tension to form air pockets that aid buoyancy.
Hydrophobicity	Where the properties of the molecule seemingly repel water, it is described as hydrophobic. In some studies, this is referred to as the plastic particles "Wettability" (Waldman & Rillig, 2020).	

Table 2 – A summary of key properties to assess plastic particles in the landscape that may provide information on its ability and present tendency to produce microplastics.

Practical Application of the Methodology

To ensure that the methodology outlined may be readily applied, a summary sheet and log sheet for recording the data have been provided as supplementary material (Supp. 1 and 2). The bar along the top of the sheet (Fig. 12) aids in recording the precise location, therefore the environment, and in-situ information of the study site. The first column allows for numeration of the plastic particles, whilst the second narrow column may be used to indicate which items may be related or composite, which is explained and demonstrated in Supplementary Material 2. The objects axes in each direction are then recorded, which in turn defines the dominant shape as sphere, disc, rod, or blade (S, D, R, or B respectively). The total number of through holes, blind holes, and closed holes are recorded under "All" T, B, and C, and the holes that the user considers to define the shape as most important are then recorded under "Dominant" T, B, and C. If the total number of holes is the same in both "All" and "Dominant", draw a line through the "Dominant" T, B, and C columns. If the object's material is known, it may be recorded under "Material", followed by recording of Mass, Volume, and Absolute Density. Once two are known, equations for determining the third are in Supplementary Material 2. Finally, color, texture density and intensity, roundness, and properties are recorded. The properties ought to be recorded such that the dominant properties that define the dominant behavior of the item are listed first or circled, with secondary properties following. In other information, if the item can be named then it is listed here along with any other key characteristics that are not otherwise recorded in the framework. Any further categorizations needed may be added to this framework, such that the data set will best serve the objectives of the study.

Locality______________________ Grid Reference____________________ Date_____________ Sheet____of____

No.		Axes			Shape	All			Dominant			Material	Mass	Volume	Abs. Density	Colour	Texture		Rnd	Properties	Other information
		Long ℓ	Interm. i	Short s	(S/D/R/B)	T	B	C	T	B	C		M	V	Ad		D	I			

Figure 12 – The recommended methodology for recording the data of plastic particle attributes.

Conclusions

Our understanding of plastic behavior in the environment is presently limited by our non-consistent approach to classifying and recording objects and particles. Through adopting learnings from sedimentology and extending the observational principles, we have developed a unified and universally applicable objective classification scheme, which is scale-independent and may be used in any environment. The scheme may be applied to any plastic item, even extended to describe a range of materials and composites beyond plastic, as importantly, plastic is not the only anthropogenic component of concern in the landscape (Kiessling *et al.,* 2019). The developed methodologies describe an objective and consistent approach to assess the size, shape, absolute density and material properties of a plastic particle or item.

- For size, we compile existing schemes and adopt the nomenclature boundaries that can be meaningfully connected to function and site of accumulation.
- For shape, we quantify the dimensions to classify an overall shape, consider the texture as extended from classic sedimentological studies, and account for the number and nature of the holes in the item.
- For density, we outline the importance in assessing the absolute density of the item rather than the density of the polymer.
- For material properties, we complied key properties that have implications for an item's behavior in the environment.

The log sheet and summary sheet are both presented in the supplementary materials (Supps 1, 2). The framework methodology outlined in this paper outlines the challenge and offers an objective, methodological solution such that we can better record our findings, hence refine our understandings of the connection between physical attributes and behaviors of plastic in the environment. While primary users of this approach may be dominantly interested in the dynamics of particles within landscapes, the insights derived from this scheme will also hold significant value for a broader range of stakeholders, including those focused on clean-up efforts. Our focus on objective classification enables the multidisciplinary usability of the scheme, such that both scientific and social learnings may be drawn from the data. It can deliver detailed insights into the types and behaviors of plastics encountered, the data can contribute to a unified database and enable us to understand human- and nature-driven source-to-sink routing of plastic globally and in the environment. As such, we, as a community, will be able to draw broader conclusions that will be integrated with an environmental understanding of plastic.

Future Work

The present limitation to this methodology is arguably in its complexity, however, we are not yet able to reasonably simplify the methodology as we do not have the data to establish how much precision we need in these studies. As such, we must manage the complexity for now as if simplification occurs before we understand the implications of the parameters, we will be limiting our observations and potential for understanding. Additionally, we recognize that elements of the methodology are over-simplified, such as where complexity of a plastic particle is high, its shape and form is quantified quite reductively. Extensive thought was provided to this challenge, and it was not workable to add further complexity to the framework method, so we recommend that any additional complexities needed are added to the framework principles. The parameters considered in this study will significantly aid in populating our understanding of variability of plastic in the environment and how its properties may connect to its behaviors. Through better clarifying the properties and characteristics of plastic items, we can provide insight into knowledge gaps relating to probabilities of plastic behavior (e.g., Khatmullina & Chubarenko, 2019), and how particles behave with characteristics such as elasticity. Lastly, we recognize that other disciplines have different requirements and priorities that are essential for their research questions, and in terms of environmental monitoring, the methods that have been developed are very appropriate. As such, we recommend that this classification acts as a unifying framework onto which findings from monitoring events may be mapped, such that the results may be interrelated to other studies and contribute to understanding how plastic will behave as a sediment. In conclusion, the presented classification scheme is a well-integrated solution to a major ongoing challenge across many communities and disciplines and provides a framework from which many critical inquiries may be advanced.

Competing Interests

The authors have no competing interests to declare.

Supplementary Material

Locality______________________ Grid Reference___________________ Date____________ Sheet____of____

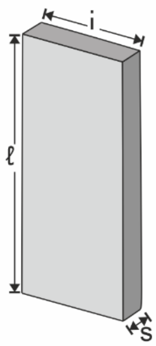
No.		Axes			Shape	All			Dominant			Material	Mass	Volume	Abs. Density	Colour	Texture		Rnd	Properties	Other information
		Long ℓ	Interm. i	Short s	(S/D/R/B)	T	B	C	T	B	C		M	V	Ad		D	I			

Summary sheet for classifying plastic as a sediment

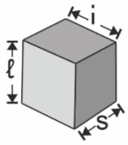
Item 1
Item 2
Item 3

Multiple joined particles are a "compound" item. Describe each item separately and indicate that they are related through using the narrow column on the log sheet. In a set of 3 (or more) items, the first and second boxes will be filled in the lower and upper halves respectively and the middle box(es) entirely filled.

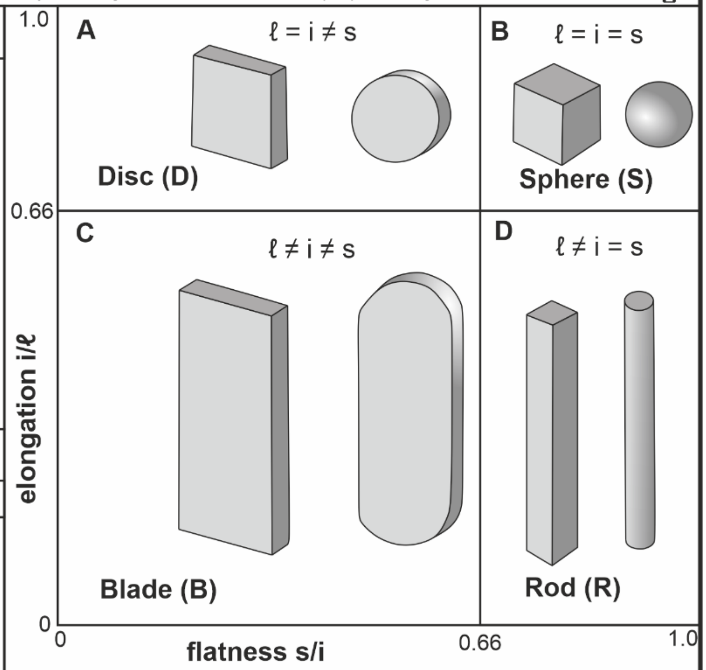
Dimensions



Nanoplastic (≤1 nm - 1 µm)
Microplastic (1 µm – 5 mm)
Mesoplastic (5 mm – 5 cm)
Macroplastic (5 cm – 1 m)
Megaplastic (1 m – 10 m)
Gigaplastic (≥ 10 m)

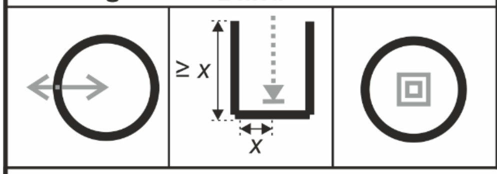


The longest measurement in each direction is recorded.



Types of Hole

Through | Blind | Closed

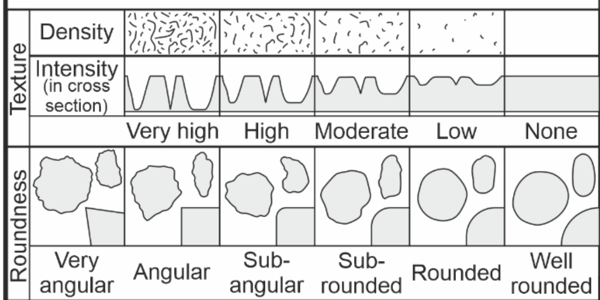


Hole Notations

- Number of holes : Through; Blind; Closed = TnBnCn
- If a number exceeds 10 as 10+, e.g., T10+B0C0
- If the item is opaque but at least one closed hole is suspected notate with "?" e.g., T0B0C?1+
- If the material is more hole than solid, notate as "net" e.g., TnetB0C0
- If the material is not solid, but more solid than hole, notate as "por" for porous e.g., TporB0C0

Dominant holes are the ones that define the structure of the item. It is interpretive so may be a factor of function.

Surface texture & roundness



Absolute density, mass, and volume

Absolute Density = $\frac{\text{mass}}{\text{volume}}$

Mass = absolute density x volume

Volume = $\frac{\text{mass}}{\text{absolute density}}$

Colour

The dominant colour of the item should be recorded and if there is no colour, record as "colourless".

Material Properties

O - Opacity No light can penetrate the particle itself.	**T - Transparency** Some to almost all light can penetrate the particle.
B - Brittleness Breaks under stress without significant deformation.	**P - Plasticity** Can be permanently deformed without breaking.
S - Softness Can be readily marked by another object.	**H - Hardness** More able to withstand surface indentations.
F - Flexibility May be repeatedly stretched without breaking.	**E - Elasticity** Returns to original size and shape post deformation.
St - Static Electricity May have a tendency to attach to other materials.	**Hy - Hydrophobicity** Where the item properties seemingly repel water.

Other Information

- If the shape is further definable (e.g., curled / twisted) or object is recognised, include details or item name here.
- Include information on the status of the item in relation to physical environment, i.e., content of sand, water, or air.
- Any biological activity can be noted here, e.g., algal films or other growths / interactions with fauna.
- If alterations to the item exist, interpretations on the natural or mechanical derivations can be noted.

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