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Review

Plastic litter affected by heat or pressure: A review of current research on remoulded plastic litter

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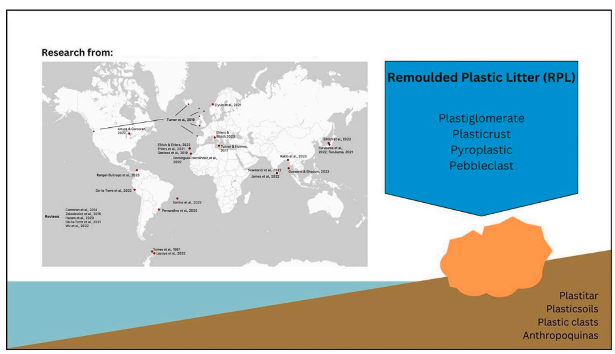
HIGHLIGHTS

- Nomenclature for remoulded plastic litter is used inconsistently in the literature.
- Remoulded plastic litter (RPL) is proposed as an umbrella term.
- Ecotoxicology and exposure to all classes of RPL represent enormous research gaps.
- Implementation of RPL in monitoring programs is important.
- RPL has been reported from many different locations, but there are huge knowledge gaps.

GRAPHICAL ABSTRACT



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ABSTRACT

Pyroplastic, plastiglomerates, anthropogenic rocks, plasticrusts, pebble clasts, plastitar, plastisoil and anthropoquinas are examples of terms that have been used to describe the secondary products of plastic litter that have been melted, moulded, pressed, or cemented together with other plastic litter and/or minerogenic sediments or organic matter, either naturally or anthropogenically. Such processes may also favor the formation of new geological features containing plastics, such as coastal landforms or sedimentary rocks. Further research and classification of this secondary plastic litter is critical for understanding the implications of this emerging contaminant as well as to create well-targeted measures to reduce it. The literature review as presented includes 32 peer-reviewed articles published between 1997 and June 2023, all of which describe various burnt or otherwise remoulded plastic litter from around the world. Based on our review we propose a new umbrella term for the different forms of secondary plastic litter that have been modified by heat or pressure: Remoulded Plastic Litter (RPL). If accepted by the research community, important steps for future research and policy will be to implement RPL into the OSPAR protocol for monitoring and assessment of marine litter and thereby fill knowledge gaps of the geographic distribution of RPLs and their potential toxicities to nature and humans. It is clear that the distribution of RPL research spans the globe, however, studies in Africa, Oceania, large tracts of the polar regions, and terrestrial areas in general, are scarce to absent, as are ecotoxicological studies and recommendations for policy development.

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1. Introduction and research aim

How to regulate and mitigate plastic waste entering oceans and inland waters is indeed a wicked problem (Wagner, 2021); policy decisions depend on high-quality, reliable data and insightful research with clear conclusions. Plastic litter is an enormous global issue (Geyer et al., 2017) and vast amounts are also regularly burned (Velis and Cook, 2021), on purpose or accidentally, creating new sub-classes of plastic waste. An emergent class of plastic litter produced from exposure to heat and/or pressure via natural and anthropogenic processes, often termed pyroplastic, has been an infrequent subject of scientific study over the past several decades, yet important enough to be considered and named in reports used to support policy decisions for the regulation and mitigation of plastic waste. This particular class of secondary plastic litter (which we differentiate from the secondary nano- and microplastics generated from macroplastic litter) has different polymer structures, morphologies, embrittlement/preservation properties, and potentially new ecotoxicological pathways compared to the original plastic waste from which it was formed (Corcoran et al., 2014; Ehlers and Ellrich, 2020; De-la-Torre et al., 2022; James et al., 2022; Sudhakar et al., 2008). Such secondary plastic litter may be combined with minerogenic sediments and organic matter during the process of its formation, and/or with other plastic waste. Rapid burial and/or trapping of plastic litter in coastal dunes, mangroves, and coral reefs are clear entry points for plastic into the geological record (Andriolo and Gonçalves, 2022; Martin et al., 2019; Menicagli et al., 2023; Turner et al., 2021) as lithification can occur rapidly here (e.g. eolianite, beachrock, etc.). In Norway, where plastic litter is a dominant feature in coastal soil stratigraphies, it has also been proposed to have influenced coastal and near-shore geomorphology by forming erosion-resistant embankments (Bastesen et al., 2021). Research into this emerging class of plastic litter is nascent; clear definitions and descriptions of the most common varieties of secondary plastic litter, their formation processes, abundance, longevity, and potential impacts on organisms, ecosystems, and on geological processes like sediment transport and deposition, are needed. Plastic litter that has been burned or exposed to heat and pressure might also be more vulnerable to microbial colonization (James et al., 2022), or break down more easily, which may lead to an increase in the rate of production of microplastics (De-la-Torre et al., 2022). As such, the primary aim of this article is to review the state of knowledge of plastic litter that has been burnt or exposed to heat and/or pressure in the natural environment by natural or anthropogenic processes. Our secondary aim is to put forward a new umbrella term to cover most of the different forms of secondary plastic litter that have been named in the literature so far; that is Remoulded Plastic Litter or RPL. Lastly, we put forward a first attempt towards a simple, user-friendly structure for classifying the different forms of plastic litter that fall under the RPL umbrella. Acceptance from the scientific community of an umbrella term and nomenclature for such secondary plastic litter is important for its inclusion in global monitoring programs and policy regulations. Rangel-Buitrago et al. (2022) previously advocated for a highly detailed nomenclature, but as this review shows, the number of studies on the different sub-classes of RPL is limited, and in terms of policy and standardization, a clear and simplified nomenclature without too many sub-categories may be a better option for now.

2. Methods

The literature review as presented includes comments, notes, and letters, as well as research articles and reviews from a total of 32, peer-reviewed articles. This review is classified in between a state-of-the-art review and a systematic review, as discussed below (Grant and Booth, 2009). Search strings were applied within the search engines PubMed, Web of Science, and Google Scholar. All articles found using PubMed and Web of Science were also found using Google Scholar. The search was carried out between the 6th and 10th of June 2023 and began with an initial search for articles where the word 'pyroplastic' occurred in the title ("intitle:pyroplastic"). This yielded 53 results in Google Scholar, four of which were relevant in terms of the title of the article. Most of the studies that resulted from this search were not focused on pyroplastic litter, but rather on materials science applications, for example, on the deformation of porcelain tiles (e.g. dos Santos Conserva et al., 2017). If the title of the article did not provide enough information with which to determine the scope of the article itself, the abstract was read. The search was followed by "intitle:pyroplastic pollution", which produced ten results. The search string "intitle:plasticrust" produced one result and "intitle:'novel plastic' pollution" yielded two relevant articles. To expand the search to include plastic litter in the marine environment that has been exposed to heat and/or pressure, the search strings "pyroplastic marine debris" and "pyroplastic marine waste" were applied in Google Scholar. These searches produced 86 and 130 hits, respectively, but resulted in only two new relevant articles.

As second and third steps, the articles found to contain relevant information by reading the title and looking at the abstract were read in full, and their citations of other relevant articles were used as a reference for further investigation. This strategy is known as an "ancestry approach" search for relevant research (Russell, 2005). Complementary to the searches, some articles that the authors were already familiar with from beforehand, or received information about from colleagues, are included even though they did not appear in the searches. Such articles were included due to the chief aim of the review, which is to gather as complete a list as possible of all the current research on the theme, rather than being as strict as possible regarding the search string and its hits.

Most studies found because of the ancestry approach reported RPLs as a secondary observation made during research into an unrelated plastic-waste issue; that is, most studies did not set out to study plastic litter that has been exposed to heat and/or pressure during or after release into the natural environment, but rather, came across it by chance and reported it incidentally. These studies were nonetheless included with the aim of trying to give an overview of the global distribution of RPL.

Quality assurance of our review process follows that presented by Boote and Beile (2005), who developed a literature review scoring rubric that categorizes the different steps of the review process into: coverage, synthesis, methodology, significance, and rhetoric. Each of these steps are scored on a scale of one to four. A score of one, for example, might be a literature review that does not discuss criteria inclusion or exclusion (coverage), key vocabulary is not discussed (synthesis), research methods are not discussed (methodology), and is poorly conceptualized (rhetoric). A score of four, on the other hand, justifies the inclusion and exclusion of literature in the literature review (coverage), critically examines the state of the field (synthesis), critiques and introduces new methods to address problems with predominant methods (methodology), and is well developed and coherent (rhetoric) (Boote and Beile, 2005). In the review presented here, we have aimed to score no less than three and preferably four, in all aspects (see Boote and Beile (2005) for their detailed scoring rubric).

2.1. Analysis of the articles included in the review

All articles were analyzed in terms of the research aims (see Section 1). In practical terms, this meant examining and condensing the information describing the motivation for the research, the collection and analysis of the data, interpretation of results, and the relevant literature cited in each article. Due to the low numbers of articles, the analysis was mostly conducted qualitatively but with elements of quantification regarding the number of articles that mentioned certain issues or concluded in certain directions.

Each article was analyzed on the basis of an initial selective coding (step A), which considered the type of publication (e.g. review or research article), motivation(s), type of data collected, geographic area (s) covered, methods for analysis, main findings and conclusions, recommendations, and degree of representativeness, in order to systemize the data and be able to further analyze it. This process of creating themes is consistent with Cohen et al.'s (2007) process for finding superior categories in a text. The next step (step B) included a qualitative evaluation of meaning and content based on reading the articles and creating brief summaries. In the third step (step C) of the analysis, an inductive approach was taken to create a large number of codes based on the content summaries produced in step B (this step of the analysis is not presented as a table or appendix as part of the article). The final step (step D) involved the merging of similar codes and creating multiple categories, with some of these (considered the most important and relevant) presented as findings and results in our review, described as main themes and thereby sub-themes. The inductive process applied here is inspired by the description of the inductive coding process in Thomas (2006). To enable a discussion of the findings in broader terms than those supported by the final categories obtained (step D), codes and text elements from the previous steps (A–C) were read and analyzed again, working backwards from the final step D. The coding was performed in Microsoft Excel. Broad initial categories within the selective coding (step A) were chosen because of the wide variety of the research and the emergent nature of this field of study, which has led to a diverse variety of methods, conclusions, and recommendations. Table 1 presents the metadata and the context of each article analyzed.

3. Results and discussion

In total, 32 papers were investigated (Table 1), with most of them focusing on evidence of a new form of plastic litter found in different locations around the world; in other words, studies focused on the registration of a new substance within a specific region and, to some degree, its quantification and/or analysis.

Based on the geographical distribution of results (Fig. 1), it is clear that the distribution of RPL is widespread, however studies from Africa, Oceania, and large areas of the polar regions, including Canada, Russia, and Greenland, are scarce to absent. There is also a lack of research from inland areas. Furthermore, when we look at the number of objects identified in the result from India (Goswami and Bhadury, 2023), for example, little information about the situation in this region is given, with only one RPL identified.

Six of the articles can be described as reviews, however, the first is already outdated (Zalasiewicz et al., 2016) and the second is a short communication that briefly reviews some of the literature but does not critically evaluate it nor identify research gaps or propose nomenclature (Chowdhury et al., 2023a, 2023b). The third and fourth reviews are considered mini reviews (Haram et al., 2020; De-la-Torre et al., 2021), with Haram et al. (2020) including a brief presentation of relevant nomenclature (*The plasticene lexicon*) but without advocating for significant changes or standardization. The fifth review article by Wu et al. (2022) have a main focus on microplastics in intertidal zones rather than on RPL, but mention plastiglomerate. The sixth and final review article included in our literature review is a viewpoint article by Rangel-Buitrago et al. (2022), who propose an updated plastic cycle comparable to the geological cycle. Rangel-Buitrago et al. (2022) do not overlap with the literature review presented here, since they propose a large number of names and definitions, and do not appear to aim to simplify the nomenclature for RPL to facilitate improved research and cooperation with NGOs, citizen scientists, governments, and environmental agencies, but rather, make it comparable to that used in the geosciences.

The superior raw data file from the data analysis, including the text underneath each selected category, is presented in a descriptive way throughout this combined Results and discussion section. It includes citations from the different articles as well as qualitative interpretations and condensations presented underneath each selected category within the analysis framework (Step A). The pre-defined, selected categories are presented as the headings for each of the five subsections.

Step C in our analysis revealed 357 new categories, but as this is raw data and many of these categories overlap, they are not presented here. Thirty-five superior-headline categories (the result of Step D) were created inductively from the 357 categories of thematically organized content presented in Section 3.2. The content within these categories is discussed subsequently. The publishing dates span the years 1997 to 2023. Names and definitions are included in this section as they are also considered results from the literature review.

3.1. Names and definitions

As a new field of research emerges, it is important to create a descriptive and appropriate vocabulary to begin the process of generating nomenclature consensus within the research community. Accepted nomenclature and terminology are especially important to enable the clear and effective communication of results to policy makers, NGOs and public authorities. Based on steps A–D of our analysis, the main terms for secondary plastic litter that have been modified due to exposure to heat or pressure are listed below. Next to each term (in bold) definitions and our recommendation for future use are discussed. Finally, the umbrella term for this class of secondary plastic litter, RPL, is defined.

Pyroplastics are described by Turner et al. (2019) as plastic litter with a matrix that appears to have been formed by burning or melting and without a uniform morphology. The color is further described as homogeneous, often black or gray, sometimes with hues of green, blue, pink, or yellow (Turner et al., 2019). Pyroplastic particles are described as less angular, often agglomerated, with surfaces characterized by cracks, cavities, pits, and fractures, and for which the material appears to be weathered (Santos et al., 2022). James et al. (2022) argued for the creation of a subcategory of 'partly pyroplastic', defined as plastic waste with external pyroplastic properties but without changed internal polymer properties. Wu et al. (2022) describes pyroplastic as a subtype of plastiglomerates, but this seems inappropriate, especially in cases where the pyroplastic does not include any sand, pebbles, or other mineral or organic inclusions (see below). Pyroplastic has also been described as modified plastic by Rangel-Buitrago et al. (2023) and Santos et al. (2022) has put forward the term 'clast' as the geological analogue for a fragment of pyroplastic as well as 'clastic plastistone' when the material is homogeneous.

Rangel-Buitrago et al. (2022) divide different plastic forms into different umbrella terms based on their origin, where pyroplastics end up as a "modified plastic" affected by elevated heat and weathering, and they do not consider whether the secondary plastic contains a mix of other substances (e.g. sand or pebbles). As the terms modified plastic and clastic plastistone seem somewhat heterogenic, we hereby propose that the term pyroplastic is retained for only plastic litter that has been melted or thermally deformed and where the majority of the material is plastic and does not contain other organic or minerogenic materials. For a photographic example see Rangel-Buitrago et al. (2023) page 5.

Plastiglomerates are high- or low-density plastic that have been thermally altered and contain organic and/or inorganic materials such as gravel, sand, or cobbles (Corcoran et al., 2014). A distinction is made between in situ vs. clastic types of plastiglomerates: clastic describes a matrix of melted plastic and organic/inorganic elements, whereas in situ describes melted plastic adhered to a larger cobble or boulder (Corcoran et al., 2014). In situ plastiglomerates with a high-density matrix (1.7–2.8 g/cm^3) increases their potential for burial in sediments (Corcoran et al., 2014). Furukuma et al. (2022) propose a sub-type of plastiglomerates named "clastic/in-situ plastiglomerates" which are formed from melted plastic containing inorganic and organic elements attached to a cobble or boulder. The proposed geological analogue is a conglomerate (Santos et al., 2022). We propose that the distinction between clastic, in situ and clastic/in-situ plastiglomerates is excluded from the nomenclature, but otherwise keep the Corcoran et al. (2014) definition. We also recommend that the organic and minerogenic inclusions in the plastiglomerate are described, as is the density. For a photographic example see Rangel-Buitrago et al. (2023) page 4.

Table 1
Articles found in the literature review. Full references provided in the Reference List. The articles that are highlighted in orange were found to be published in a predatory journal according to Beall's list (https://beallslist.net/) or found to be of insufficient level of quality in terms of erroneous citations or a high degree of similarity with another article.

Author	Year	Title	Type of research	Journal	Theme	Geographical Location where stated
Torres et al.	1997	Beach debris survey at Cape Shirreff, Livingston Island, during the Antarctic season 1996/97	Report	CCAMLR Scientific Abstracts	Plastic debris on Livingston Island	Cape Shirreff, Livingston Island, Antarctica
Turner & Holmes	2011	Occurrence, distribution and characteristics of beached plastic production pellets on the island of Malta (central Mediterranean)	Research article	Marine Pollution Bulletin	Microplastics on beaches	Malta
Corcoran et al.	2014	An anthropogenic marker horizon in the future rock record	Research article	GSA Today	Formation, identification and analysis of plastiglomerates	Kamilo Beach, Hawaii, USA
Zalasiewicz et al.	2016	The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene.	Review	Anthropocene	The geological cycle of plastic	Review
Gestoso et al.	2019	Plasticrusts: A new potential threat in the Anthropocene's rocky shores	Article	Science of The Total Environment	Formation of plasticrusts	Madeira, Spain. Rocky shores
Turner et al.	2019	Marine pollution from pyroplastics.	Research article	Science of the Total Environment	Pyroplastic	Samples supplied from Orkney Islands (Scotland), Vancouver (Canada), and Spain.
Ehlers & Ellrich	2020	First Record of 'plasticrusts' and 'pyroplastic' from the Mediterranean Sea	Note	Marine Pollution Bulletin	Registration of "new" plastic materials in nature	Giglio Island, Italy. Intertidal rock and sandy beach
Corcoran & Jazvac	2020	The consequence that is plastiglomerate	Comment	Nature Reviews Earth and Environment	Comment on how plastiglomerates is a sign of the plastic crisis	No data
Haram et al.	2020	A plasticene lexicon	Mini review	Marine Pollution Bulletin	Plastic terminology	Literature
Fernandino et al.	2020	Anthropoquinas: First description of plastics and other man-made materials in recently formed coastal sedimentary rocks in the southern hemisphere.	Baseline article	Marine Pollution Bulletin	Costal sedimentary rock containing plastic	Rio Grande do Sul, Brazil. Wave dominated coast
Cyvin et al.	2021	Macroplastic in soil and peat. A case study from the remote islands of Mausund and Froan landscape conservation area, Norway; implications for coastal cleanups and biodiversity	Research article	Science of The Total Environment	Macroplastic in soil	Norwegian coast. Near shore soil and peat.
Ehlers et al.	2021	Plasticrusts derived from maritime ropes scouring across raspy rocks	Note	Marine Pollution Bulletin	The process of formation of plasticrusts	Madeira, rocky intertidal.
Furukuma[a]	2021	A study of 'new plastic formations' found in the Seto Inland Sea, Japan.	Research article	International Journal of Scientific and Research Publications	Pyroplastic	Seto Inland Sea, Japan. Slightly rocky natural coast
De-la-Torre et al.	2021	New plastic formations in the Anthropocene	Review	Science of The Total Environment	Review of new plastic forms	Literature
Ellrich & Ehlers	2022	Field observations in pebble beach habitats link plastiglomerate to pyroplastic via pebble clasts.	Research article	Marine Pollution Bulletin	Plastiglomerates and pyroplastic	Madeira, Spain. Pebble beach.
De-la-Torre et al.	2022	First record of plastiglomerates, pyroplastics, and plasticrusts in South America.	Research article	Science of The Total Environment	Surveying of heat influenced plastic at four beaches in Peru. Pyroplastic, plastiglomerates and plasticrusts	Peru
James et al.	2022	Divergent Forms of Pyroplastic: Lessons Learned from the M/V *X-Press Pearl* Ship Fire	Research article	ACS Environmental Au	Pyroplastic nurdles from a burning cargo ship transporting nurdles	Container ship on fire, polluting coast of Colombo, Sri Lanka
Santos et al.	2022	Plastic debris forms: Rock analogues emerging from marine pollution	Research article	Marine Pollution Bulletin	Creation of anthropogenic rock	Trinidade Island, Brazilian offshore
Arturo & Corcoran	2022	Categorization of plastic debris on sixty-six beaches of the Laurentian Great Lakes, North America	Letter	Environmental Research Letters	Classification of plastic debris	Laurentian Great Lakes, North America
Furukuma et al.	2022	Frequent observations of novel plastic forms in the Ariho River estuary, Honshu, Japan.	Research article	Science of The Total Environment	Observations of plastiglomerates and pyroplastic	Japan, river estuary
Wu et al.	2022	Intertidal zone effects on occurrence, fate and potential risks of microplastics with perspectives under COVID-19 pandemic	Review	Chemical Engineering Journal	Microplastic as a result of protective equipment. Risk of microplastic impacted by different intertidals. Formation of plastiglomerates	Literature
de Vos et al.	2022	The M/V X-Press Pearl Nurdle Spill: Contamination of Burnt Plastic and Unburnt Nurdles along Sri Lanka's Beaches	Letter	ACS Environmental	Burned plastic nurdles from ship catastrophe	Sri Lanka

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Type of research	Journal	Theme	Geographical Location where stated
Domínguez-Hernández et al.	2022	Plastitar: A new threat for coastal environments	Short Communication	Science of The Total Environment	Formation of a new plastic formed by microplastic and tar; named plastitar	Canary Islands, Spain
Sewwandi et al.	2022	Unprecedented marine microplastic contamination from the X-Press Pearl container vessel disaster	Research article	Science of The Total Environment	Microplastic contamination from container vessel disaster	Sarakkuva, Sri Lanka
Lozoya et al.	2022	Stranded pellets in Fildes Peninsula (King George Island, Antarctica): New evidence of Southern Ocean connectivity	Research article	Science of The Total Environment	Stranded pellets, (Microplastic)	King George Island, Antarctica
Furukuma et al.	2022	Frequent observations of novel plastic forms in the Ariho River estuary, Honshu, Japan	Research article	Science of The Total Environment	Quantification of pyroplastic and plastiglomerates	Ariho River estuary, Honshu, Japan
Rangel-Buitrago et al.	2022	The Plasticene: Time and rocks	Viewpoint	Marine Pollution Bulletin	Proposal of updated plastic cyclus and new geo-nomenclature	Literature
Rangel-Buitrago et al.	2023	Decoding plastic pollution in the geological record: A baseline study on the Caribbean Coast of Colombia, north South America	Baseline article	Marine Pollution Bulletin	Plastic as part of the geological record	Central Caribbean Coast of Colombia
Ellrich et al.	2023	Plasticrust generation and degeneration in rocky intertidal habitats contribute to microplastic pollution	Research article	Science of The Total Environment	Plasticrust as a source of microplastic	Sea of Japan Coast
Chowdhury et al.[b]	2023	Impacts of emerging and novel plastic waste variants on marine and coastal ecosystems: Challenges and implications on the circular economy	Primer article	WIREs Energy and Environment	Literature walk-through about novel and emerging plastic contaminants. Pyroplastic and plastiglomerates as one them	Literature
Rakib et al.	2023	First record of plastiglomerate and pyroplastic pollution in the world's longest natural beach	Short communication	Science of The Total Environment	Plastiglomerates and pyroplastic identification and quantification	Cox's Baxar beach, Bangladesh
Chowdhury et al.[c]	2023	Emerging plastic litter variants: A perspective on the latest global developments	Short communication	Science of The Total Environment	Brief overview of the literature	Literature
Goswami & Bhadury	2023	First record of an Anthropocene marker plastiglomerate in Andaman Island, India	Research article	Marine Pollution Bulletin	Occurrence of plastiglomerates	Andame Island, India

[a] Furukuma (2021), is published within a journal that appears on Beall's list of predatory journals. The article is analyzed together with the others.
[b] Chowdhury et al. (2023a) was excluded from further analysis due to insufficient citations and strong statements without literature to back up the statements.
[c] Chowdhury et al. (2023b) was excluded from the further analysis due to high degree of similarity with De-la-Torre et al., 2021, when it comes to both content, use of sources as well as structure.

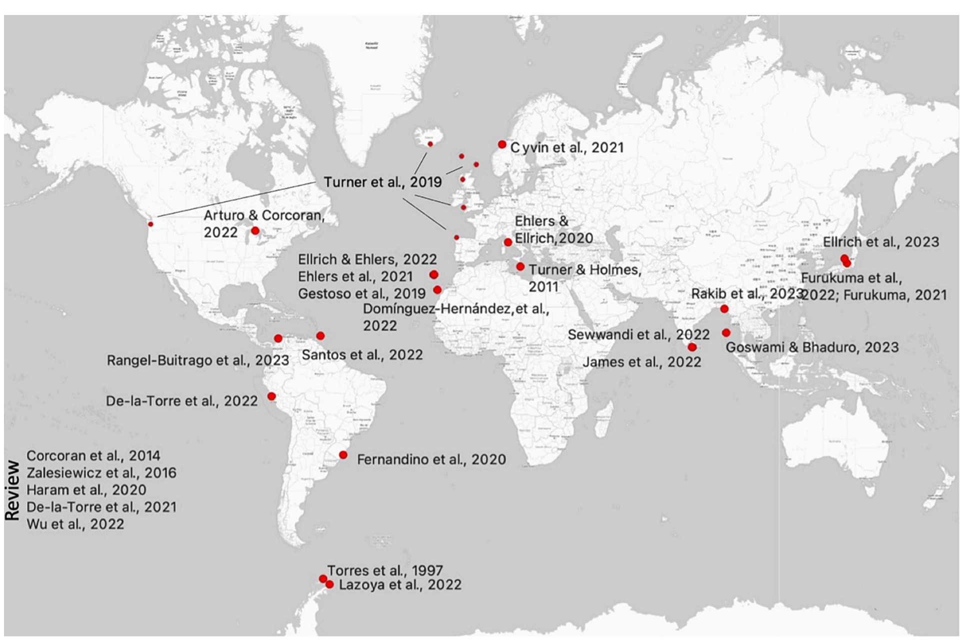

Fig. 1. Map of the locations included in the 32 reviewed studies. Made by the Authors. Basemap: OpenStreetmap, 2023. A list of review articles included in our review that are not tied to one area or region are placed in the South Pacific Ocean.

Pebble clast is described in the literature as a morphological feature of plastiglomerates (Ellrich and Ehlers, 2022), where pebbles or gravel that have subsequently been eroded from the plastiglomerate, have left behind only the melted plastic, but with the form of the pebble still visible. This process creates a characteristic morphology with casts and molds from the original particle that has since been released from the plastic matrix. Pebble clast is proposed here as an official morphological sub-type of/descriptor for plastiglomerates. For a photographic example see Ellrich and Ehlers (2022) page 3.

Plasticrusts are described as plastic that covers rock surfaces, likely created by hydrodynamic deformation of plastic debris on high-energy coasts, leaving traces that adhere to the rock surface (Gestoso et al., 2019). The assumption that plasticrusts are formed from hydrodynamic power is supported by Ehlers and Ellrich (2020), who proposed that their distribution may therefore be influenced by the tidal amplitude, wave exposure, and marine debris concentration. These parameters can thus, potentially be predicted. The polymer composition of plasticrusts has been found to include PE, HDPE, PP, and HDPE-PP (Ehlers and Ellrich, 2020; Ehlers et al., 2021). Wu et al. (2022) proposed that plasticrusts, like pyroplastic, are included as a sub-division of plastiglomerates. We propose to reserve the term plasticrust for situations where plastic litter has adhered itself to a bedrock surface via hydrolic pressure versus a plastiglomerate, which may have a different process of formation (for example exposure to heat, melting,) and necessarily contains organic and/or inorganic inclusions. For a photographic example of a plasticrust, see Gestoso et al. (2019) page 414.

Plastistone is an umbrella term introduced by Santos et al. (2022) that includes both plastiglomerates and pyroplastics. By incorporating methods from stratigraphy and sedimentology Santos et al. (2022) describes how plastic has become a part of the geological cycle and proposed lava flowstone as an analogous geological term for plastistone. The term plastistone is scarcely found in other literature besides Santos et al. (2022) and we suggest that it is too poorly defined at this time to be considered further. For a photographic example see Rangel-Buitrago et al. (2023) page 5.

Rangel-Buitrago et al. (2022) proposed 19 different subclasses of what they term, **plastic rocks**, building on existing nomenclature from sedimentary geology. The Rangel-Buitrago et al. (2022) article does not refer to Rangel-Buitrago et al. (2022) and their the 19 subclasses of plastic rocks, but argue that an updated nomenclature is needed due to the abundance of plastic in geological features. As long as research on new plastic forms is still in its infancy it is important to keep the nomenclature transparent and easy to implement into for example, global beach surveys or new policies developed for plastic litter mitigation and monitoring. Creating an over-complicated nomenclature may create obstacles to understanding the scope of the issue and it will be practically too time-consuming to gather very heterogeneous data within global monitoring programs like the beach litter monitoring protocol from the Oslo and Paris Convention (OSPAR).

Plastitar is a material that was already described in 2011 by Turner and Holmes, and again by Domínguez-Hernández et al. (2022). Tar results from oil spills, where evaporation leads to the formation of a high-viscosity, petroleum-based material, that, in the marine environment, sticks to stable and semi-stable coastal features like bedrock outcrops, cobbles, and boulders. When there is plastic stuck to or blended into tar it is termed plastitar (Turner and Holmes, 2011; Domínguez-Hernández et al., 2022). The plastic in and of itself does not need to be re-shaped, re-polymerized or changed in any way by heat or pressure, although it could be. As such, we propose to leave plastitars outside the umbrella term, RPL (see definition below) for secondary plastic litter that has been exposed to heat or pressure. We also suggest to keep plastitar as a subdivision of tar, rather than including this material in to the plastic pollution research, as the material and it's properties are likely more influenced by the tar than the plastic litter it contains. For a photographic example see Domínguez-Hernández et al. (2022) page 5.

Whereas plastiglomerates most often develop as a result of anthropogenically-derived heat (such as that from campfires), **anthropoquinas** are created by natural processes in which sediments are cemented together by plastic together with $CaCO_3$ (Fernandino et al., 2020). Zalasiewicz et al. (2016) compared plastic within the stratigraphy of an anthropoquina with microfossils, in that the varieties can be used as markers for different phases of the Anthropocene. The parallel geological term may be coquina. Like coquina, anthropoquinas are formed as human artefacts are cemented in sedimentary rock, and it seems overcomplicated to describe this with a specific term as the material is just a description of plastic within the stratigraphy. This form of plastic should rather be classified as a type of plastistone rather than a type of RPL, as long as the amount of plastic meets a certain threshold. Such thresholds are so far not discussed within the literature, but percentage of plastic versus soil is often used to describe the amount of plastic within soils (Cyvin et al., 2021) and we propose volume to be a more appropriate measure than mass due to the heterogeneous densities of different polymers. For a photographic example see Fernandino et al. (2020) page 4.

Anthroposols – plastic soil. Rangel-Buitrago et al. (2023) describe plastic soils or anthroposols as a soil type containing a high degree of plastic throughout the soil column. An example of a plastic soil includes landfill used to build cities and infrastructure with/on, but similar soils were found in nature by, for e.g., Cyvin et al. (2021) and Bastesen et al. (2021). As long as the plastic litter in the anthroposoil has not been chemically altered by heat or pressure, it should not be considered further here, but we recommend that different classes of plastisoil with their own terminology and classification system to be developed. A distinction has already been proposed to differentiate anthrosol (mixture of natural soil and plastic waste) from plastic clasts, however, these terms will not be considered further here. For a photographic example see Rangel-Buitrago et al. (2023) page 6.

3.2. Umbrella term: remoulded plastic litter (RPL)

We propose remoulded plastic litter, or RPL, as an umbrella term for: pyroplastics, plastiglomerates (with pebble clast retained as a sub-class or descriptive term for a specific morphology of plastiglomerates), and plasticrusts. Anthroposoils are proposed as a second umbrella term, with anthropoquinas and plastisoils as subdivisions of anthroposoils. Specifically, when plastic is incorporated in soil, but has not undergone such a methamorphosis, we propose the term plastisoil, but these anthroposoils will to little degree be discussed further in our review. We recommend that the terms plastistone and plastitar to not be included under the RPL umbrella; in the case of plastistone, because of limited usage in the literature so far and a general lack of research, and in the case of plastitar, because it does not necessarily fit the prerequisite for inclusion (i.e. that the plastic litter inclusions must be chemically or structurally altered by heat or pressure). See Table 2 for proposed simplified nomenclature.

The 19 definitions with three umbrella terms proposed by Rangel-Buitrago et al. (2022) give an interesting overview of the possibility to merge geology and plastic litter nomenclature, but the level of detail and sometimes forced connections to geological terms seems counter-productive within a nascent field of research dominated by a great deal of interdisciplinarity, involvement of citizen scientists, and desperate need for mitigation policies based on global and local knowledge of the scope and impacts of plastic pollution. We suggest that the level of detail and parallels to geological terminology in Rangel-Buitrago et al.'s (2022) nomenclature system may be an obstacle to generating reproducible and comparable results within the field of plastic pollution and would like to consider further the choice of parallel geological terms vs. for example, archaeological terms.

3.3. *Described motivation for research (category A, Table 3)*

Motivating factors described within the articles include insufficient

Table 2
Proposed simplification of current overall nomenclature, with space for further development as the body of literature increases.

Remoulded plastic litter (RPL)			Anthroposoil		
Plastiglomerate Pebbleclast	Pyroplastic	Plasticrust	Plastic soil	Plastic clast	Anthropoquinas

knowledge of plastic as a part of the geosphere (Santos et al., 2022); lack of knowledge about plasticrusts in general (Ehlers and Ellrich, 2020) and more specifically, the processes responsible for the formation of plasticrusts (Ehlers et al., 2021); and lack of knowledge from a specific area or biome (Furukuma, 2021; Cyvin et al., 2021). The main motivations for the research presented in the 32 articles was a lack of research (Table 3; A1) about the topic or about specific locations or environments (Torres et al., 1997; Turner and Holmes, 2011; Ehlers and Ellrich, 2020; Ehlers et al., 2021; Furukuma, 2021; De-la-Torre et al., 2022; Furukuma et al., 2022). A lack of information about fate, formation process(es) or impact of the new substances, and a wish for a discussion about the new plastic forms as a part of the geologic cycle (Corcoran et al., 2014; Santos et al., 2022) were also listed, as well as a wish for a general discussion on current literature within the field (Corcoran and Jazvac, 2020; Furukuma et al., 2022).

The registration of novel information or "firsts" is also described as a motivation for publishing research (A2), for example: the first report on burnt plastic (Turner et al., 2019), first registrations of plasticrust in general (Corcoran and Jazvac, 2020), plasticrust in Madeira (Ehlers and Ellrich, 2020), the first description of anthropoquinas or plastiglomerate (Fernandino et al., 2020; Ellrich and Ehlers, 2022), the first study on the cleaning of nurdles from beaches (Sewwandi et al., 2022), or the first report of plastic in the geological record from the central Caribbean coast of Columbia (Rangel-Buitrago et al., 2023). First registration of new plastic forms or a predictive model, are also described as motivations for research (Gestoso et al., 2019; Zalasiewicz et al., 2016). It is natural that these "firsts" are included as motivation for the studies as they become the foundation for future research, but publishers and authors should be cautious about overemphasizing firsts, rather than conducting research or publishing articles that contribute to a broadening and deepening of our knowledge about already known issues. Although a lot of research about RPL will have a diminishing ability to be "the first study on…", their importance may obviously increase as comparisons become possible and new knowledge gaps emerge. "The first study on…" should therefore not be a criterium for publication, nor something that makes a manuscript more publishable.

The possibility to highlight a global environmental threat or avoid further pollution (A3) is also described as a motivating factor (e.g. Ehlers and Ellrich, 2020; Cyvin et al., 2021; Torres et al., 1997) as are more specific environmental issues like the importance of clean lakes (Arturo and Corcoran, 2022) or the effect of the X-press Pearl catastrophe (Sewwandi et al., 2022). Finally, a lack of terminology (Haram et al., 2020) and need for new nomenclature (Rangel-Buitrago et al., 2022) were described as motivating factors for research into RPL (A4).

3.4. *Data material and analysis method (category B, Table 3)*

FTIR is the most frequently used analytical method (B1) for object identification and/or analysis (Turner and Holmes, 2011; Gestoso et al., 2019; Ehlers and Ellrich, 2020; Ehlers et al., 2021; De-la-Torre et al., 2022; James et al., 2022; Santos et al., 2022; Arturo and Corcoran, 2022; Furukuma et al., 2022; Wu et al., 2022; Sewwandi et al., 2022; Rangel-Buitrago et al., 2023; Ellrich et al., 2023; Rakib et al., 2023). Less frequently used in plastic identification are micro-Raman or Raman analysis (Cyvin et al., 2021; Goswami and Bhadury, 2023), and a combination of Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), HSB (hue, saturation, brightness) colometry, and X-ray fluorescence (element composition) (Fernandino et al., 2020; Sewwandi et al., 2022; Turner et al., 2019).

The most used descriptive method for identifying plastics (B2) is visual analysis, but color classification, densitometry, and floatation are also common (Turner and Holmes, 2011; Furukuma, 2021; James et al., 2022; Lozoya et al., 2022; Furukuma et al., 2022). Sampling strategies are highly variable, and range from observations, transect studies, opportunistic gathering, citizen science approaches, collection from specific areas to non-specific surveys of all kinds of litter, sampling of quadrants and categorization in a variety of different categories. The reporting on temporal resolution and number of locations investigated also vary greatly (B3). The sample number of pieces of RPL (B4) investigated or observed ranges from one or two (Goswami and Bhadury, 2023; Rangel-Buitrago et al., 2023) to more than twenty thousand (although only of a fraction of those analyzed were found to actually be thermally altered; Arturo and Corcoran, 2022).

Summarizing these heterogenous results, demonstrates a clear need for common parameters to be evaluated to enable the comparison of results between studies and regions. FTIR is widely used, and it seems natural to maintain it as the gold standard for analytical analysis, while also acknowledging the value of big data sets (e.g. citizen science) with less detail about polymer composition. At the same time it is interesting that Pyrolysis-GC–MS is not used more widely to evaluate the chemicals associated with the new plastic forms. There is also a lack of description about the cut-off between library spectra and particles approved as a specific polymer (e.g. Gestoso et al., 2019; Arturo and Corcoran, 2022). This should in general be implemented into future studies and guidelines. Studies with high temporal resolution combined with long time-series of observations are also lacking from the current body of literature.

3.5. *Main findings and conclusions (category C, Table 3)*

The overall impression from a broad examination of the 32 articles included in this review is that RPL is widespread globally, yet there is currently insufficient data with which to comment on the severity of the problem, patterns of distribution, favoured environmental compartments (e.g. coastal sediments), fate, and potential threats and impacts on individual biota and ecosystems. As an example, of the studies reviewed that used multiple transects as a method of data capture (e.g. De-la-Torre et al., 2022; Furukuma et al., 2022), it is still not possible to compare their findings with global litter counts, like the EU baseline dataset 2015–2016 (European Commission, 2020) as the methods differ.

Little is known about the abundance and chemical composition of pyroplastics and plastiglomerates, although some studies in this review concluded that concentration in coastal environments is dependent on wave exposure, tidal amplitude, and temperature and frequency of campfires (C1, Table 3; Ehlers and Ellrich, 2020; Furukuma et al., 2022). New, thermally-affected plastic forms have been discovered with a variety of polymers like HDPE, LDPE, PP, PE, HDPE, LDPE, LLDPE, PA, PET (Goswami and Bhadury, 2023; Rakib et al., 2023; Furukuma et al., 2022; De-la-Torre et al., 2021). Color and degradation do not necessarily correlate across the studies, and degradation may be external, but not internal. A wide range of plastiglomerate densities have also been noted, from less than 1.0 g/cm^3 to 1.7–2.8 g/cm^3 (respectively Furukuma et al., 2022; Corcoran et al., 2014). It has also been questioned whether surveying is so far underestimating the distribution of some RPL, due to camouflaging colors and the morphology of some thermally degraded plastic forms (Santos et al., 2022; de Vos et al., 2022; Turner et al., 2019).

In terms of category C2, chemicals (Table 3), plastic normally not

Table 3
Method Step D: the final 5 main themes (A–E) from the inductive coding process. Thirty-five subthemes are indicated by a number following the main theme letter: A1–A4; B1–B4; C1–C9; D1–D13; E1–E5. By coding the major themes and dividing into various sub-themes, the state-of-knowledge of this emerging class of plastic litter can be clearly discussed and critiqued, and knowledge gaps identified (see Sections 3.3–3.7). See Table 1 for list of articles.

Motivation for research (A)	Lack of research (A1)	Descriptions from the authors of "first registration" or first research about (A2)	Highlight a global environmental issue (A3)	Need for new nomenclature (A4)									
Data/methods (B)	Analytical methods (B1)	Descriptive methods (B2)	Sampling/analytical strategies (B3)	Number of objects identified (n=) (B4)									
Main findings and conclusions (C)	Concentration/abundance (C1)	Chemicals (C2)	First evidence of (C3)	Impact (C4)	Source, formation process, or reason for occurrence (C5)	Marker of the Anthropocene (C6)	Nomenclature (C7)	Cleaning of nature (C8)	Interference with biota (C9)				
Recommendations for further research or policy (D)	No recommendations (D1)	Mitigation (D2)	Distribution (D3)	Formation process (D4)	Ecotoxicology and effect on biota and environment (D5)	Stratigraphy or geological marker (D6)	Policy (D7)	Requests for action towards change (D8)	Human nature interaction (D9)	Standardization and cooperation (D10)	Risk evaluation (D11)	Decomposition (D12)	Raising awareness (D13)
Weaknesses and strengths interpreted (E)	Sampling (E1)	Number of objects/sites investigated (E2)	Novelty (E3)	Use of analytical methods (E4)	Recommendations (E5)								

only consists of hydrogen and carbon, bound together as a pure polymer, but also includes other chemicals, such as flame retardants, colorants, and other additives, which change the polymer properties. The broad range of polymer compositions, polymer blends (Ellrich and Ehlers, 2022), and pyroplastic materials, such as those created by campfires, shows that there is a large variety of polymers that may depend on global and/or local production and consumer behavior.

Plastic is inevitably entering the food web, as it is now found within all geographical areas globally. Empty snail eggs have been observed attached to pyroplastic and barnacles attached to plastiglomerates, for example (Furukuma et al., 2022). Cadmium and lead were documented in burnt nurdles from UK beaches (Turner et al., 2019), while brominated flame retardants (BFRs) were found in pyroplastic, although to a small extent (Turner et al., 2019). De-la-Torre et al. (2022) hypothesized possible leaching of BFRs from pyroplastic, however increased levels of Polycyclic Aromatic Hydrocarbons (PAHs) were found in pyroplastic (James et al., 2022). The absence of BFRs is hypothetically connected to the flame resistance of polymers blended with BFRs. Increased levels of Potentially Toxic Elements (PTEs) were found in sand from beaches polluted with pristine as well as thermally affected nurdles (Sewwandi et al., 2022). Potentially negative impacts of plasticrusts on intertidal organisms has also been flagged by Gestoso et al., 2019. To summarize, the chemical blend of plastic is even more complicated when we deal with RPL, and there is currently little knowledge of its influence on biota, ecosystems, and humans.

With respect to category C3 (Table 3), there were many instances of 'first evidence of…' in the main conclusions of the 32 reviewed articles. These ranged from geographic (e.g. first evidence of burnt plastic on Antarctic beaches by Torres et al., 1997), to coining terminology (first use of plastitar by Domínguez-Hernández et al., 2022), to the discovery of new forms (e.g. anthropoquinas by Fernandino et al., 2020). One of the latest firsts was first pyroplastic reported from India (Goswami and Bhadury, 2023); few observations were reported here with limited implications for further research in the region.

All plastic litter, including RPL, may impact organisms in the natural environment (category C4, Impact; Table 3; De-la-Torre et al., 2021; Gestoso et al., 2019; Turner et al., 2019). There is in general, very little known about the possible effects of RPL on biota based on our review, however, limited knowledge of this topic has resulted in a high degree of hypotethisizing. Investigations into the impacts of RPL on organisms and ecosystems with environmentally realistic RPL concentrations/polymers are highly recommended.

C5, Source, formation process, or reason for occurrence: Abiotic factors is influencing the occurrence of RPLs. Onshore wind is found to be positively correlated with greater amounts of pyroplastic on beaches (Furukuma et al., 2022) as well as sheltering islands protecting the coast reduced the plastic pollution at the shoreline but also contributed to greater prevalence of pellets backshore within swash zones (Turner and Holmes, 2011). Pyroplastic in general is found to have a density below one while it is also hypothesized whether formation of gas-bobbles during burning/heating could change the density (Furukuma et al., 2021). The ultimate sources of different RPLs is not thoroughly investigated within current research literature available, but some is known. Approximately 20 % of plastiglomerates were found to have as a source from the fishing industry, and the density was found to be 1.7–2.8 g/cm3 (Corcoran et al., 2014). Plastiglomerate is also reported to accumulate on rocky surfaces as times passes (Gestoso et al. (2019), in parallel to what is found about plasticrusts, also increasing in abundance (more accumulation than weathering), concentrating on angular rocks and more susceptible to breaking down into microplastics after only days (Ellrich et al., 2023). But we do not know what is the ultimate source of this plastic objects creating these RPLs.

In category C7 (Nomenclature), we note that multiple authors advocated for nomenclature and standardization of describing new types of plastic litter (e.g. Haram et al., 2020; Santos et al., 2022). Rangel-Buitrago et al. (2022) have proposed a nomenclature that parallels that used by geologists. When it comes to the theme of cleaning up pollution (category C8, cleaning of nature), mechanical treatment of sand polluted with plastic nurdles from a ship catastrophe was deemed a successful method (Sewwandi et al., 2022). There are too few studies to discuss the interface with biota (category C9) but it has been hypothesized that organisms grazing on rocky surfaces might be affected by plasticrust (De-la-Torre et al., 2021). There are also reports of snail egg capsules and juvenile barnacles attached to pyroplastic (Furukuma et al., 2022).

With category C6, Stratigraphy/geological marker, plastiglomerates are considered by Corcoran et al. (2014) a part of the rock record and a marker of the Anthropocene. Plastic litter in general has the potential to be used as an age marker in stratigraphy, comparable to microfossils (Zalasiewicz et al., 2016), and which also extends to RPL. Antropoquinas and plasticrust are threats to geodiversity as they are coloring our coastlines and entering geological cycles (Fernandino et al., 2020; Gestoso et al., 2019).

3.5.1. Summary of category C: main findings and conclusions

The area of rocky beach covered by plasticrusts is increasing with time (Gestoso et al., 2019). Fishing lines and ropes (Corcoran et al., 2014; Ehlers et al., 2021) appear to be the primary source of plastic for plasticrusts, while plastiglomerates and pyroplastic most likely originate from campfires and legal and illegal burning of garbage, and therefore presumably, consumer goods and food packaging (Corcoran et al., 2014; De-la-Torre et al., 2022). With increasing production of plastic, and therefore also increased potential for pollution, it is likely that global plasticrust abundance will continue to increase, leading to coloring of the coastline and young sedimentary rocks, as well as increased visibility in the stratigraphic record.

3.6. Recommendations for further research or policy (category D, Table 3)

Seven studies included in this review do not make any recommendations for further research or policy (D1), however, systems to prevent pollution, as well as mitigation strategies and reduction of single-use plastic have been proposed by several authors (Corcoran and Jazvac, 2020; Fernandino et al., 2020; Rangel-Buitrago et al., 2022; Rakib et al., 2023) (D2). Careful cleanups that avoid the creation of plasticrust when plastic is dragged along rocky shorelines, for example, are encouraged (Ellrich et al., 2023). Questions about the cost vs. benefit of these measures should be considered, as it will probably take more time to clean gently.

More information about global distribution as well as more regional distributions of RPL (D3) is also called for (Gestoso et al., 2019; Ehlers and Ellrich, 2020; Domínguez-Hernández et al., 2022; Lozoya et al., 2022; Goswami and Bhadury, 2023), and specifically more research about formation processes of plastitar are encouraged (D4) (Domínguez-Hernández et al., 2022). As plastitar does not fall under the umbrella of RPL, we will not comment further on this.

None of the studies included in this review have investigated the ecotoxicity of RPL, however multiple studies point out the importance of such research (see category D). The unusually dramatic language used to describe our gap in knowledge regarding ecotoxicity of RPL in peer-reviewed literature should be taken seriously by governments and policymakers. For example, more research has been asked for on: the importance of plasticrust and its impact on adjacent foodwebs (Gestoso et al., 2019); the ecotoxicological effects of pyroplastic (James et al., 2022); and the effects of plastitar on marine coastal environments (Domínguez-Hernández et al., 2022) (D5). Exploration of the formation biofilms and possible health risks associated with chemicals from nurdle pollution (as well as burned/thermally deformed nurdles) are also mentioned (Sewwandi et al., 2022) (D5). Finally we note that research on burning conditions and the release of toxins, and on the role pyroplastics might have on pathogen transport, antibiotic-resistant genes, and invasive species are lacking in current literature (see De-la-Torre et al., 2021).

The requirement for naming the current geological stage "the time of plastic" is, according to Rangel-Buitrago et al. (2022), now met, and they further describe this plastic stage comparable to the Triassic-Jurassic Extinction (D6). Soils with a high degree of plastic content (i.e. Cyvin et al., 2021) have been described as a hallmark of the Anthropocene and proposed as a global chronostratigraphic standard for naming this period in earth history (Rangel-Buitrago et al., 2023).

Ellers and Ellrich (2022) state that there is a critical need for implementation of this new category of plastic litter into policy action plans (D7), and while we fully support this, propose broad categories, rather than more specific ones. Plasticrust, for example, has been named as a new possible category within OSPAR and National Oceanic and Atmospheric Administration (NOAA) protocols for plastic monitoring (Gestoso et al., 2019) and Turner et al. (2019) argued that burned plastic should get a new classification in litter surveying guidelines (D7). We also encourage to act now, in terms of taking the Anthropocene seriously (D9: Rangel-Buitrago et al., 2022) and encourage policy development (D8: Corcoran and Jazvac, 2020).

Standardization and cooperation (D10) are essential (Goswami and Bhadury, 2023; Rakib et al., 2023; Haram et al., 2020; De-la-Torre et al., 2021) and the importance of cooperation with material scientists has been proposed as a possible way forward (Rakib et al., 2023).

More research into the interaction of rocks, seawater, other abiotic factors upon plastiglomerates and their biofouling effect (Wu et al., 2022), as well as the possible interaction between plasticrust and rock-dwelling organisms are needed (De-la-Torre et al., 2021) (D11). Sewwandi et al. (2022) highlighted the need for more knowledge about the decomposition of plastic nurdles (D12), and Rakib et al. (2023) mention the importance of raising awareness (D13) through long term educational/informational programs. We agree that all of these needs are relevant, especially the standardization of methods in order to be able to compare research, as well as inclusion of RPL into monitoring protocols to be able to track temporal development and change. Policies to prevent the free burning of plastic are also important, but must start with the creation of infrastructure for the transport and treatment of plastic waste, a cultural change towards circularity, and creation of national and international mitigation strategies (Fernandino et al., 2020; Hellevik and Cyvin, 2023).

3.7. Weaknesses and strengths interpreted (category E, Table 3)

Many articles reviewed here do not provide enough details on sampling methods, lack detailed methodological descriptions, or they are studying a very limited geographical area, with or without a systematic sampling approach, making it difficult to assess the severity of the issue and global distribution of RPL (E1). At the same time, most studies document a limited number of objects that we would classify as RPL, making the studies interesting as a first start looking into this field, but with limited possibility to assess the severeness of the problem, distribution, or representativeness of findings, even locally (E2). Journal editors should take this issue seriously, prioritizing studies that repeat existing studies or broaden our knowledge of geographical distribution or toxicity, while they limiting studies with just a few opportunistically gathered samples of RPL described, including those reported as the "first observation" of an RPL from a specific small area.

Most of the studies in our review lack recommendations for future research or policy, however, some are quite thorough on this matter. We hereby propose policy recommendations as a semi-obligatory headline within journals' "guide for authors". There are descriptions of the situation as a crisis, but few studies come up with ideas for how to handle this crisis. We also encourage the development of a common language, as current nomenclature is inherited from a mixture of multiple disciplines by researchers with different backgrounds. Due to the inherent multidisciplinarity amongst authors researching plastic pollution, including RPL (and amongst the journals that publish this research), many of the articles in our review claim novel findings, but taken as a whole, this field of research must be seen as premature (E3).

The common ground is that policymakers need to take this theme seriously and create internationally-binding treaties (as recently discussed by Hellevik and Cyvin (2023)), at the same time as researchers should support and implement a straightforward nomenclature and expand research into possible toxicity and severity of RPL as an emerging pollutant.

3.8. Representativity

What is representative, does in general depend on the scale. Two analyzed objects might be representative for one square meter, as would a survey of an entire coastline throughout an entire year, revealing only a few, or even no RPL. Nonetheless, the number of objects identified and/or examined was low within most of the studies included in this review. A low number is not necessarily a problem in itself, but taken together with the low number of studies, there is no real knowledge of the global situation or severity. The study by Arturo and Corcoran (2022) registered thousands of objects in separate categories (excluding an RPL category), but even so, their results suggest that RPL is not widely distributed along the shorelines of the Great Lakes of the USA and Canada. Adding a separate category for RPL into monitoring programs like OSPAR and NOAA protocols (www.orpar.org; www.noaa.org) would be an important step towards getting a better sense of the severity and distribution of RPL.

4. Summarizing perspectives and the way forward

A common finding from most of the studies evaluated in this review is the lack of conformity in terms of sampling strategies, methods, and scale, with the single exception of the use of FTIR for identifying the type of plastic. Nevertheless, without common ground for what is accepted as an appropriate FTIR-spectra match between library and scanning, the low number of RPL samples investigated (with some exceptions, e.g., Turner et al., 2019; De-la-Torre et al., 2022), in combination with a lack of consensus on terminology, it is impossible to say anything about the RPL across regional to global scales, much less evaluate the distribution of the different classes of RPL.

Studies of the ecotoxicological effects of RPL are non-existent, thus, it is impossible to comment on the potential toxicity of RPL to biota, ecosystems, and human health. There is good evidence, however, for large amounts of plastic being burned globally, each year (Velis and Cook, 2021). Moreover, pyroplastic, which is much more chemically complex than its pure counterpart, has been found to contain lead, cadmium, and increased levels of PAH (Turner et al., 2019; James et al., 2022).

Several researchers have urgently recommended the inclusion of RPL into national and international policies or surveys (Ehlers & Ellrich, 2019; Gestoso et al., 2019; Turner et al., 2019). As research develops in the future, it may be useful to further subdivide pyroplastics, plasticrusts, and plastiglomerates into different categories, but a complicated language combined with little knowledge about their distribution, formation, and ecotoxicology, makes it today more useful to refer to an umbrella term like RPL.

In terms of non-RPL, namely, anthroposoil, we recommend that a threshold for when soil is defined as natural or anthropogenic (i.e. at what percentage by weight or volume of plastic is a soil classified as an anthroposil) is defined. In the study of coastal soils from Norway, by Cyvin et al. (2021), soil containing from 3 % to approximately 70 % of plastic (dry weight/dry weight; dw/dw) appears visually to be a fully, plastic-infiltrated soil when reaching the higher percentage. A concentration of substantially lower percentage should therefore be considered as a plastic soil step-in threshold. As a point of departure for the discussion of this threshold, we propose a level of 5 % plastic/soil (dw/dw). An examination into volume vs. weight for measuring percent content of low-density polymers, like EPS, is also warranted.

Remoulded Plastic Litter, anthropoquinas, and anthroposols affect the color of our coastlines and we recommend future social science studies into the impact of this on our collective view of nature and humans, as well as local aesthetic concerns. Without more information about the global occurrence and proportion of total plastic waste from RPL and other secondary plastic litter forms and products, it remains difficult to evaluate their possible impacts. The body of research so far indicates that, despite large uncertainties, the possibility for chemical leaching from plastic litter is high (De-la-Torre et al., 2022; Turner et al., 2019; James et al., 2022), there is a clear anthropogenic influence on geology and Earth surface processes and landforms (Zalasiewicz et al., 2014; Corcoran et al., 2020; Rangel-Buitrago et al., 2022), and therefore also an influence on geodiversity (Fernandino et al., 2020; Rangel-Buitrago et al., 2022). Plastic, including RPL, is a marker of the Anthropocene (Corcoran et al., 2014; Zalasiewicz et al., 2016; Rangel-Buitrago et al., 2022; Rangel-Buitrago et al., 2023) and becoming a part of our future heritage, coloring our shorelines and stratigraphy around the world (Smykowski and Stobiecka, 2022; Rangel-Buitrago et al., 2023). These findings, in connection with the precautionary principle, make it our obligation to conduct further research within this emerging field, as well as to implement global measures to mitigate the pollution. Knowledge of ecotoxicological effects of the different RPL is needed as is an accepted nomenclature and inclusion of RPL into protocols and databases.

CRediT authorship contribution statement

Jakob Bonnevie Cyvin: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francis Chantel Nixon:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francis Chantel Nixon reports financial support was provided by Norwegian University of Science and Technology. Francis Chantel Nixon reports a relationship with Norwegian University of Science and Technology that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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