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Review

Transdisciplinary pragmatic melioration for the plastic life cycle: Why the social, natural, and technical sciences should prioritize reducing harm

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ABSTRACT

Plastics underpin modern society but also threaten to choke it. Only 9 % of all plastic waste is recycled, usually with loss of quality ("downcycling"); the rest is landfilled or dumped (79 %) or incinerated (12 %). Put bluntly, the "plastic age" needs a "sustainable plastic culture." Consequently, we urgently need to develop a global and transdisciplinary approach not only to fully recycle plastics but also to manage the harms across their life cycle. The past decade has witnessed an explosion in research on new technologies and interventions that purport to help solve the plastic waste challenge; however, this work has, in most cases, been carried forward within single disciplines (for example, researching novel chemical and bio-based technologies for plastic degradation, engineering processing equipment innovations, and mapping recycling behaviours). In particular, although there has been vast progress within individual scientific fields, such work does not address the complexities of various plastic types and waste management systems. Meanwhile, research on the social contexts (and constraints) of plastic use and disposal is rarely in conversation with the sciences to drive innovation. In short, research on plastics typically lacks a *trans*disciplinary perspective. In this review, we urge the adoption of a transdisciplinary approach that focuses on pragmatic melioration; such an approach combines the natural and technical sciences with the social sciences to focus on the mitigation of plastic harms across the life cycle. To illustrate our case, we review the status of plastic recycling from these three scientific perspectives. Based on this, we advocate 1) foundational studies to identify sources of harm and 2) global/local interventions aimed at those plastics and aspects of the plastic life cycle that cause maximal harm, both in terms of planetary welfare and social justice. We believe this approach to plastic stewardship can be a showcase for tackling other environmental challenges.

1. Introduction

The invention and application of plastics is one of the technological revolutions that form the basis of our consumer society. When plastics were introduced at the beginning of the 20th century, their durability was one of their attractions. "Plastic is forever" was a promise, not a threat. Plastics are immensely useful because of their weight, strength, and resilience, thermal and electrical insulation, and resistance to water and gas. Plastic items are ubiquitous and have become entangled with almost all aspects of life. However, a future with plastics has its complications.

>400 million tonnes of plastics are produced annually (Geyer et al., 2017). Packaging comprises the largest single segment (40.5 %), followed by building and construction (20.4 %), transportation (8.8 %), and electronics (4.3 %). As can be expected from this distribution, ≈50 % of all produced plastics have a short use span (<6 months), and the remaining have a long use span (for example, 25–30 years in service). Thus, a conservative estimate is that ≈200 million tonnes of plastic waste is generated within a year (Plastics_Europe, 2022); additional tonnage is discarded from long-term items going out of service (for example, house renovation and demolition).

The potential human health and environmental harms caused by plastics, including micro- and nano-plastics and the additives used to modify plastic properties, are of increasing concern (Chae and An, 2018; North and Halden, 2013; Prata, 2018; Suran, 2018; Vethaak and Leslie, 2016). Moreover, poor waste management means that an estimated 79 % of all plastics ever produced end up in landfills or are directly discarded into the environment (Geyer et al., 2017). Rising politi-

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cal awareness of these challenges has resulted in a push for a binding global plastics treaty; the second intergovernmental negotiating committee session for this treaty will meet in Paris in May–June 2023 (Intergovernmental_Negotiating_Committee, 2023). Plastic "waste hierarchies" (Leone et al., 2017) rank the different ways of dealing with our plastic waste (an example is provided in Fig. 1).

Our current plastic problem is technology and modernity related; it springs from the unanticipated consequences of the unchecked production and use of these "modern" materials. In this, plastics are not unique. The "goods" of modernity have been accompanied by "bads"—toxicity, pollution, and environmental destruction (Beck, 2010; Beck and Ritter, 1992). However, techno-optimism continues to dominate the larger societal approach to these problems, with the "belief in human technological abilities to solve problems of unsustainability while minimizing or denying the need for large-scale social, economic and political transformation" (Barry, 2016). In general, such an approach follows a linear model, by which scientific discoveries are to be translated into engineering solutions and adopted socially into real-world contexts through behaviour change (Feenberg, 2009). Social science research has critiqued this model, showing how technology exists in a complex social field; such research points out to the need for technological design and innovation to reckon with and incorporate this social field (Alexander and Rutherford, 2019; Liboiron, 2021). Nevertheless, such recognition for engagement with social, political, and economic context through what is, in effect, interdisciplinary involvement, is rarely built into the practice of the natural or technical sciences. Even when steps are taken toward such engagement, as for example in contextual engineering (Witmer, 2020), it is largely confined to the design stage and does not extend to include assessment and monitoring.

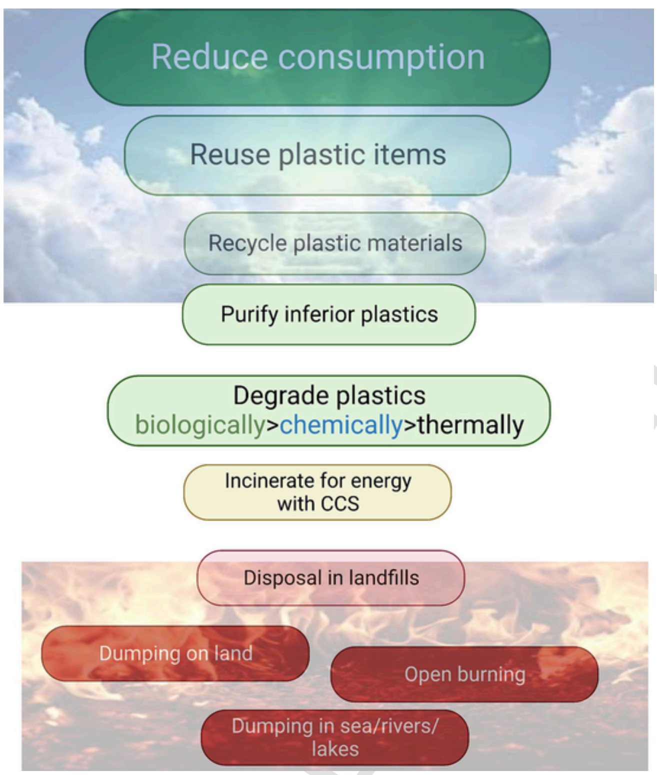

Fig. 1. An example of the plastic waste hierarchy. CCS: Carbon Capture and Storage.

The highly simplified waste hierarchy approach clearly demonstrates that an extremely broad set of research disciplines is needed to tackle the problem. These span from fundamental science (to invent new and much-needed technologies to modify plastics), to designers and engineers (to establish facilities and implement applications), and to the legal, social (to assess and incorporate social, political, and economic contexts), and pedagogical sciences (for eco-literacy campaigns). In addition to this, biologists, toxicologists, ecologists, and medical and public health experts are needed to map out the human and environmental consequences of plastic production, use, and disposal. This interplay between disciplines is summarized in Fig. 2. These disciplines will also need to work together to generate public awareness and political willingness to undertake broad-based change. No single research branch alone can solve the plastics challenge.

Here, we bring together perspectives from the natural sciences (D.E.O), technical sciences (M.H), and social sciences (G.S·P) to highlight the need for harm reduction oriented, lifecycle-based interventions and solutions that are locally adapted to the material and social ground realities of plastic production, use, and disposal. To do so, we first provide a brief overview of the material properties of plastics, as foundational information necessary for transdisciplinary studies of plastics. Then, we use the case of waste recycling and management to illustrate the interlocking challenges that necessitate both upstream and downstream transdisciplinary harm reduction. Finally, we elaborate on this approach, which we term *transdisciplinary pragmatic melioration*.

2. What are plastics?

"Plastic" is a common word covering a myriad of different materials. As a first division, plastics can be classified as thermoplastics or thermosets. Thermoplastics can be melted and reshaped, whereas thermosets are cross-linked ("cured") and cannot be reshaped after curing.

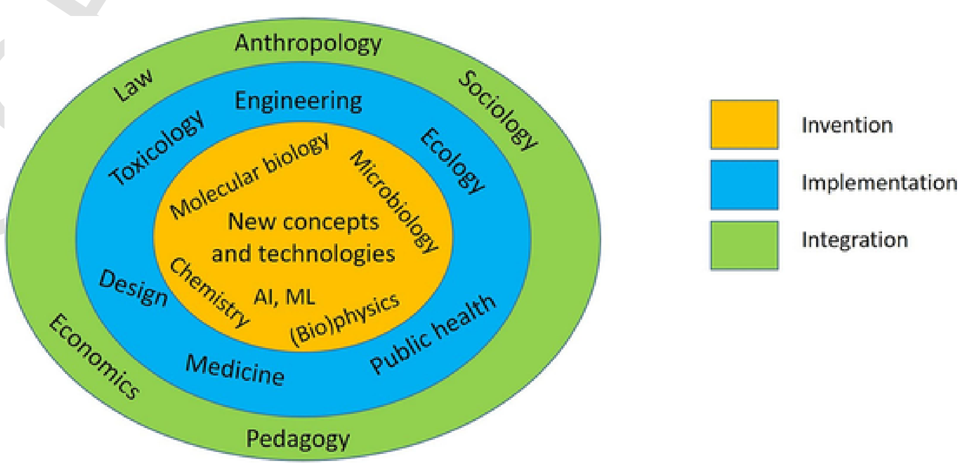

Fig. 2. The connection between different disciplines working together toward a sustainable plastic culture. AI: Artificial Intelligence, ML: Machine Learning.

These two groups can be subdivided according to their monomer or polymer components. Thermosets are divided into polyurethanes (PUR), epoxies, silicones, and so on. Thermoplastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), poly (vinyl chloride) (PVC), poly (ethylene terephthalate) (PET), and so on. Plastics can also be divided into groups based on the chemistry of their repeating unit, as illustrated in Fig. 3.

Group I plastics have carbon–carbon (C—C) bonds in their polymer backbone, that is, PE, PP, PS, and PVC. **Group II** plastics contain non-carbon atoms, such as oxygen (ester bonds in PET) and nitrogen (amide bonds in PUR). The properties (for example, mechanical, stability, processing, visual) of pure polymers are often adjusted with additives. These additives include physical fillers (for example, sand or chalk), strength-giving fillers (for example, glass or carbon fibre), softeners or plasticizers, UV stabilizers, antistatic agents, flame retardants, and dyes and pigments, among others, depending on the application. For example, glass fibre-reinforced epoxy is used for wind-turbine blades to allow them to absorb/withstand wind forces, UV absorbers are added to automotive parts (for example, the dashboard) to withstand sunlight, construction components and furniture include flame retardants, and pigments enhance the visual appeal of lunchboxes and toys. Plastics are thus generally designed and optimized for a specific product and purpose. This means that the plastic waste stream is a mixture of a breath-taking number of plastic compositions.

3. Recycling technologies and innovations

3.1. Mechanical recycling

Current mechanical recycling efforts typically involve opening, washing, sorting, cutting, and pelleting. Mixed plastic fractions are only recycled for low-value products (for example, pallets and traffic cones). Obtaining sufficient purity (95 %+) for high-end and demanding products is a challenge for mechanical recycling (Tsakona and Rucevska, 2020). The recyclers can meet this purity demand by processing either mono-component waste streams or by waste sorting. The dominant waste sorting technology is based on density (flotation sorting) and only removes polyolefins (a low-density fraction of mixed PE and PP), leaving a sinking fraction with the remaining plastics combined with non-plastic components such as sand, glass, and metals (for example, aluminium). Currently, the rising use of PET increases the sinking fraction at the expense of the recycled fraction. There is thus a paramount demand for technologies that use the sinking fraction. Among these, the enabling technology is plastic sorting, in particular, near infrared (NIR) sorting, which covers a plethora of technologies. The simpler versions employ single or dual wavelength light-emitting diodes and sensors; however, more advanced short-wave infrared camera technologies with higher success and efficiency are emerging (Faltynkova et al., 2021; Henriksen et al., 2022). The next challenge is to remove unwanted (or to pick out wanted) plastics. This is currently done by air blades and/or air nuzzles that "shoot" out the selected material to divert it from the remaining plastic waste stream. This technology is highly sensitive to waste shape, and most systems operate as flake (~10 × 10 mm) sorters. Despite encouraging successes, minimizing the number of operations required per tonne material removed still presents a challenge. More research is needed before the sorting challenge is solved and pure (95+ wt%) and ultrapure (99+ wt%) fractions can be obtained for further processing.

Part of the mechanical recycling process involves thermal reprocessing of the plastic material into pellets. As all thermal processes degrade polymers to various degrees, we still need to establish how many times a given plastic type can be recycled before it becomes mechanically inferior. Currently, mechanical recycling tends toward downcycling of plastic quality (e.g. mechanical, thermal, and rheological properties) because of contaminants, additives, and/or complex plastic mixtures. Consequently, virgin plastic often needs to be added to satisfy material standards (Schyns and Shaver, 2021).

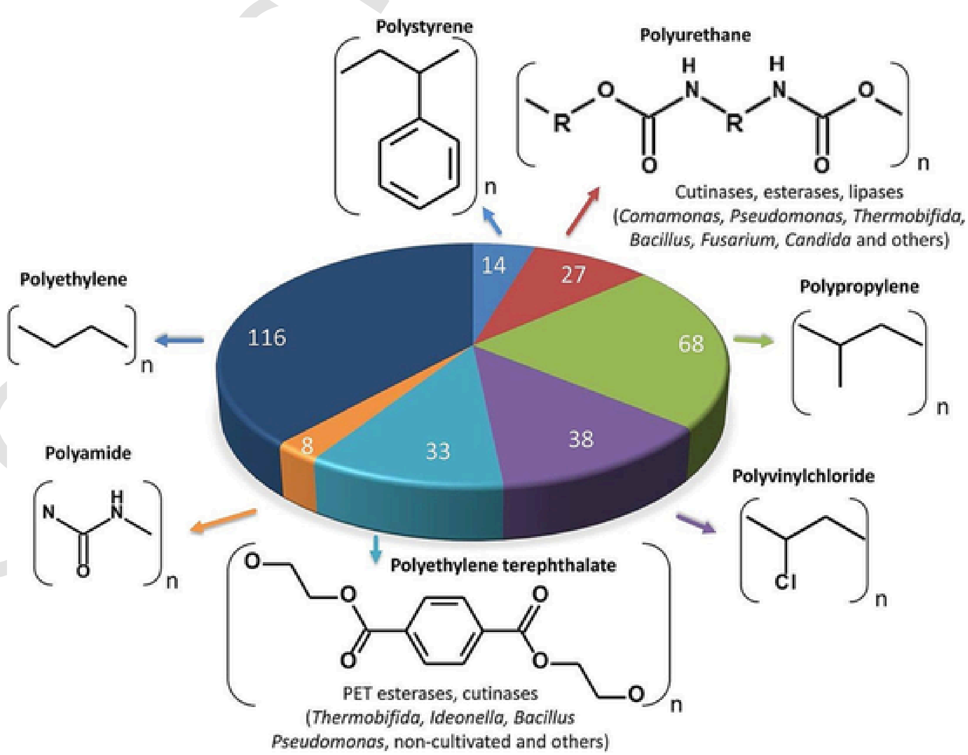

Fig. 3. The most prevalent types of plastic with the structures of the repeating units and examples of enzymes identified to be able to degrade them to smaller components. Numbers indicate million tonnes produced in 2016. Reproduced from (Danso et al., 2019) with permission under the terms of the Creative Commons Attribution 4.0 International license.

3.2. Purification

Technologies that aim to extract unwanted additives and reclaim the polymers for making new products are being developed. One promising technology is dissolution (Achilias et al., 2009; Kannan et al., 2017). The general approach is to dissolve the polymer in an appropriate solvent and then filter off pigments, remove, for example, softeners via column absorption, and so on (Kol et al., 2021; Naviroj et al., 2019). Subsequently, the polymer is extracted by precipitation, achieved by the addition of a non-solvent (Achilias et al., 2007; Ferreira et al., 2021; Poulakis and Papaspyrides, 1997). There are several obvious challenges facing this young technology, of which solvent recovery is the most pressing. In addition, dissolution is highly plastic-type sensitive; no solvent can dissolve all plastics. The technologies are still at a research level, and significant innovation is needed before they become commercially viable.

3.3. Chemical recovery

We urgently need technologies that can upcycle plastic by "resetting" it, that is, break it down to simple but high-value components that can be used afresh to build new plastics or other useful components. Degradation of plastics to their monomeric building blocks is attractive in principle but is unfortunately difficult in practice. At present, only some plastics (for example, polyoxymethylene (POM), poly (methyl methacrylate) (PMMA), PET, and some polyamides) can be degraded to monomers. We will subdivide chemical processing into pyrolysis and solvolysis. Enzymatic reconstruction, another degradation technology, involves radically different reaction conditions and will be grouped under biological degradation.

Pyrolysis is oxygen-free (anaerobic) thermal degradation of plastics. Pyrolysis shows promise for polyolefins and for yielding naphtha (liquid hydrocarbons) that can be processed in the petrochemical industry to fuels (Johnston et al., 1988; Moiseev et al., 1961). In addition, some polymers thermally degrade back to their constitutive monomers, directly providing monomers for repolymerization, for example, polyoxymethylene (POM) with almost 100 % yield to formaldehyde (Philip et al., 2008), poly (methyl methacrylate) (PMMA) with 95 % yield to methyl methacrylate (Johnston et al., 1988), and PS with ≈50 % yield to styrene (Johnston et al., 1988; Philip et al., 2008). On the other hand, PET, upon pyrolysis, undergoes a cyclization and generates vast amount of char (Holland and Hay, 2002), blocking process equipment. This process is at an industrial scale in several countries, but it is sensitive to input material and demands 80–95 % pure waste streams for useful yields. It thus presents the same sorting and purification challenges as mechanical recycling. In addition, the process is energy consuming and the product typically needs post-purification prior to use. Intense research efforts are ongoing to address these challenges.

Solvolysis uses a solvent (invariably water) as reactant or media in polymer degradation. Research is focused on either chemical degradation (breaking ester or amide bonds) or on chemically cracking the mixed plastic fraction into fuels (hydrothermal liquefaction; HTL) via thermal hydrolysis at elevated pressures. HTL degrades the plastics in sub- or super-critical water into naphtha and/or higher molecular compounds (waxes). This approach generates more fuel than pyrolysis because of free-radical chain scissions of, for example, polyolefins, while taking place under milder reaction conditions (dos Passos et al., 2020). Solvolysis has also proven valuable in the depolymerization of PET into the monomers terephthalic acid and ethylene glycol, along with different lengths of oligomers (Adschiri et al., 2011; Imran et al., 2010). It is envisioned that these monomers can be repolymerized into pristine PET. Polycarbonate (PC) studies have shown that bisphenol-A, which is the building block for new PC, epoxy, and urethane monomers, can also be obtained (Bai et al., 2020; Bozzano et al., 2012).

Although promising, more research is needed into the depolymerization of a broader span of polymers and into a process that is less sensitive to plastic purity. HTL, while less sensitive to purity, is limited by operation and reactor costs that are challenged by very low fuel and monomer prices. Finally, HTL does not recycle plastic waste back into mono-, oligomers, or plastics. Therefore, it should be considered a dramatic downcycling, only preferable to incineration for energy and heat recovery.

3.4. Enzymatic degradation

Chemical resetting is sometimes challenged by its use of corrosive and toxic reagents along with very energy-demanding reaction conditions which, with few exceptions, are environmentally and energetically unsustainable (Ragaert et al., 2017). Biological solutions are an alternative because of their mild (that is, low energy demanding) operating conditions and the enormous possibilities for improvement through engineering. A priori, one would not expect biological solutions for plastic degradation to be readily available. The vast majority (>99 %) of all human-made plastics are artificial compounds made by the chemical processing of fossil fuels, whose biological origins are hundreds of millions of years in the past and which have subsequently undergone a series of long and slow chemical–geological transmutations. Our ecosystems have not had enough time to develop tools to deal with plastics as they would deal with biological materials; there is no ready-made metabolic system in place to degrade plastics to smaller components that can be recycled in other contexts. Yet our planet's ecosystems are adaptable and versatile. There are encouraging indications that many, if not all, plastics are susceptible to biodegradation, both by microorganisms and by individual enzymes obtained from them. However, there is no one-bug-fits-all solution, as plastic degradability varies with plastic types.

Group I plastics with C—C bonds are truly alien to biology and lack obvious points of attack by normal enzymes. Before they can be dismantled to smaller pieces, they have to be made more "approachable" by oxidation. This introduces oxygen-rich chemical groups, which can then be recognized by hydrolytic enzymes and used as attack points for cleavage. Oxidation can occur either by abiotic means (typically photo-oxidation after long exposure to sunlight and air) or oxidative enzymes, such as laccases or other so-called oxidoreductases. These enzymes require helper molecules or mediators in their activity, which poses an additional challenge for efficient degradation. Overall, group I plastics present the biggest hurdle for sustainable plastic recycling. It remains to be seen whether group I plastics should be pre-treated by photo-oxidation or whether optimized oxidoreductases can do this in a competitive fashion, leaving them open to subsequent cleavage by other enzymes. There are numerous examples of microorganisms (bacteria or fungi, for example, white rot fungi which can attack tough hydrophobic polymers such as lignins in wood (Alcalde, 2015)) and invertebrates (particularly moth larvae such as the wax worm (Sanluis-Verdes et al., 2022)) able to, for example, remove plastics from surfaces and create holes in films. While it may seem appealing to use microbes or larvae as "living factories" for plastic degradation, this approach has significant drawbacks. Plastics do not lead to growth and increase in biomass of larvae unless supplemented with more ready sources of nutrients such as starch or cellulose. It is also unclear if larvae can metabolize plastics on their own or need help from bacteria present in their gut (the microbiome); in addition, we have very limited knowledge of the actual enzymes that carry out the degradation. Plastic degradation products (for example, compounds from PVC) can be toxic and thus stunt biological activity; furthermore, larvae need to be maintained in insect cultures. Often, the final breakdown of plastic fragments requires the uptake of the plastic inside the cells for intracellular conversion steps, and this can lead to bottlenecks that limit turnover. Finally, the production of large amounts of microplastics can physically compromise growth. A preferable scenario is to reconstruct plastic degradation as a series of individual steps in an open and acellular environment using pre-treated plastics together with appropriate combinations of different optimized enzymes, where both desirable degradation products and toxic side-streams can be removed in a continuous fashion (for example, by ultrafiltration).

Group II plastics contain chemical links found in biological molecules, and therefore they are in principle susceptible to natural degradation by enzymes such as esterases and amidases. The greatest progress in biodegradation has been made with PET. One of the first PETases was discovered in the bacterium *Ideonella sakaiensis*, isolated from a Japanese PET recycling station, which turned out to be a modified cutinase (an enzyme which degrades the waxy substance called cutin covering most plant surfaces) (Yoshida et al., 2016). It is not particularly thermostable, though, and this is a problem. PET degradation occurs more readily above the glass temperature (between 60 and 80 °C), where the amorphous region of PET becomes more liquid-like and thus more accessible (the crystalline phase remains unaffected as PET melts at 260–280 °C, that is, at much higher temperatures). However, various protein engineering approaches have yielded more thermostable enzyme variants. A relatively thermostable PETase (also a cutinase), which has a half-life of 40 min at 70 °C, has been isolated from leaf compost (Sulaiman et al., 2012) This enzyme is now being optimized further by multiple research groups around the world in a healthy race to develop the most effective and stable PETase. The record is currently held by a variant developed by the University of Toulouse and the company Carbios, which can degrade PET material to >90 % within around 10 h and with a cost price that is ca. 4 % of that of virgin PET (Tournier et al., 2020). Encouragingly, the material from this degradation was used to make new PET bottles of the same quality as the originals (Tournier et al., 2020). It will be exciting to see if this approach can outcompete current chemical hydrolysis strategies which are highly efficient but require higher temperatures (7 min at 250 °C) (Adschiri et al., 2011). Protein engineers have other tricks up their sleeves to improve PETase performance further, for example, by attaching "homing devices" in the form of binding domains that improve the ability of the enzymes to bind to their plastic substrates (Ribitsch et al., 2015). Finally, researchers have managed to engineer the photoautotrophic diatom *C. tricornutum* to overexpress and secrete bacterial PETase in seawater, which opens up possibilities for large-scale bioremediation efforts (Moog et al., 2019) powered by sunlight.

The enzymatic degradation of PUR is not quite as far in the development, reflecting the polymer's more complex chemical structure. It contains ester bonds and amide (urethane) bonds, and both must be cleaved for efficient recycling. Enzymes found to degrade PU largely target the ester bonds (Liu et al., 2021). However, there are intense efforts underway based on high-throughput screening from a diversity of genetic sources, and promising urethanases have very recently been identified (Branson et al., 2023). This work is also encouraged by the many high-value products that can be obtained from PU, including alcohols, acids, and aromatic precursors for the chemical industry (Liu et al., 2021).

In summary, with the exception of PET, for which scalable production facilities are currently under development, we still lack well-defined and well-characterized enzymes to attack plastics. We need to develop novel screening methods to identify new plastic degrading enzymes as efficiently as possible and to understand the molecular mechanisms by which these high molecular weight petropolymers are broken down. While such systems may, over the next decade, assume a significant role in biochemically recycling our plastic waste, they will not magically transform our current wasteful plastic consumption nor will they address the enormous amounts of micro- and nano-plastics which accumulate both on land and in the sea. Moreover, to be able to recycle plastics, we need to first become much better at efficiently collecting our plastic waste on a global scale.

4. Global waste management and recycling challenges

Around two billion people worldwide lack access to municipal solid waste collection services. Collection coverage ranges vary globally and regionally, as follows: North America, 100 %; Europe, 80–100 %; Latin America and the Caribbean, 80–100 %; Asia, 50–90 %; and Africa, 25–70 % (Modak et al., 2015). Rural areas tend to have less coverage than urban areas, including a complete lack of coverage in some cases (SWEEPNet, 2014). When there is coverage, it can be infrequent—with long wait times between collection—or inconvenient—with collection occurring at locations far away from households or small businesses (Wiedinmyer et al., 2014). Amid such patchy collection, concerns about ritual purity, hygiene, or sorcery can lead to the burning or dumping of certain kinds of wastes (for example, clothes, diapers, or sanitary pads) (Elledge et al., 2018; Guitard, 2018; Ntekpe et al., 2020). Moreover, even with waste collection coverage, low-income households (also in the Global North) may choose to burn or dump their wastes to avoid or reduce collection fees (Skumatz, 2008; Wilson and Velis, 2015).

In areas with waste collection services, the nature of those services can vary widely, from coverage through the public sector, the private sector, a mixture of both, or through the informal sector, such as micro- or small-enterprises, community-based organizations, or NGOs (Modak et al., 2015). Friction and a lack of coordination between various arms of waste collection services are common, especially in the Global South, and can result in waste leaks or open burning to reduce trash volumes or make to make wastes "go away" (Pathak et al., 2023). Complex governance regimes, resource-poor settings, and realities of corruption also mean that waste management officials across most of the globe must navigate diverse and often contradictory funding and policy directives (Ayeleru et al., 2020; Cornea et al., 2016).

An informal waste economy plays an important role in plugging the waste collection gaps left by local authorities in much of the Global South. The informal waste economy is informal in the sense that the services provided by this economy are not paid for by the state. Informal recycling economies typically comprise waste pickers, itinerant buyers, scrap dealers, and other scrap materials traders, and such an economy recovers large volumes of waste material for recycling, reducing the burden on dumping grounds and of uncollected wastes (Doron and Jeffrey, 2018; Gidwani, 2015). However, when it comes to plastics, such recovery focuses on high-value wastes, such as PET bottles, that are relatively easier to collect. Thus, smaller pieces of plastic waste, such as sachets or torn pieces of packaging, that require more labour-intensive effort to collect, wastes deposited in difficult to access areas, and plastics with lower scrap value are typically ignored.

In the Global South, the segregation of wastes for recycling usually occurs through the efforts of waste pickers, often at dumping ground sites, rather than at source. In some places, there is even active resistance to segregation-at-source as it requires thought, effort, and space from end users and households (Colon and Fawcett, 2006; Gupta and Gupta, 2015). In the Global North, where segregation-at-source is increasingly being encouraged as the norm, non-sorting behaviour and misunderstandings regarding what plastics are recyclable, how to separate them, and how to clean them abound, resulting in mixed or unclean wastes (Minelgaite and Liobikiene, 2019; Rousta and Ekström, 2013). Even when wastes are appropriately segregated, further separation (that is, to separate out different polymers from mixes) is required. Whereas technology exists for sorting at an industrial scale, for example in the case of PET bottles with PE bottle caps, reliance on manual labour is the norm in most of the world. Managing high volumes of non-biodegradable wastes is a challenge even for OECD countries, and wastes are frequently shipped to lower income countries (with lower labour costs) for segregation and purported recycling. China was the favoured destination for such shipping until 2018, when it implemented a ban on low-quality waste imports under its Operation National Sword (Matsuda et al., 2021). The policy had major consequences for international recycling, as countries in the Global North were faced with growing piles of plastic scrap that they could not process. Trade in recyclable scrap was displaced onto other low-income countries, such as Indonesia, Turkey, and Vietnam. Once shipped to these countries, wastes are segregated and cleaned, and those that cannot be recycled are often dumped or burned in the open (Cook and Velis, 2022; European_Environment_Agency, 2019; Gundogdu and Walker, 2021). The cleaning also presents problems, as lack of regulations mean that the runoff is often discharged into open sewers and the soil with obvious adverse environmental consequences.

The question of economics and resources is significant. Low- and middle-income countries typically lack adequate waste management resources. Of the total municipal solid waste generated in 2016, 93 % in low-income countries and 66 % in middle-income countries was deposited in open dump sites rather than in scientifically managed landfills that control emissions of landfill gases and leachate that otherwise enters the soil and groundwater (Sharma and Jain, 2020). Mixed wastes generate landfill gases, which are not managed at dump sites (Chavan et al., 2022), and the decay of biodegradable wastes is an exothermic process, which produces heat. Under those conditions, temperatures at dumping grounds can rise above the auto-ignition temperatures of landfill gases such as methane. Thus, these highly flammable gases can catch fire, leading to dumping ground conflagrations that wastefully feed off—and consume—high calorific-value plastic deposits.

Recovery of wastes from dumping grounds is further complicated by the fact that organized criminal gangs often wield control over these grounds and the materials there (Chatterjee, 2019; Muindi et al., 2020; Velis, 2017). Criminal involvement in waste management is not limited to control over dumping grounds in the Global South. It also negatively affects waste flows, landfill locations, and landfilling volumes in countries in the Global North (D'Amato et al., 2015).

5. The need for transdisciplinary approaches across the plastic life cycle

As the case of recycling shows, the effective implementation of sustainable technologies for plastic control will require the development and implementation of solutions that are integrated into their real-world contexts. Technological innovations in recycling that do not address waste management gaps cannot address the plastic waste crisis. Plastic waste collection, segregation, and storage systems, as well as laws and policies for their appropriate regulation, will need to be developed while bearing in mind local capacities—including, for example, waste pickers and the informal economy, constraints, and sociocultural contexts. Not just systems but also technologies will have to adapted; to be cost-effective and feasible, for example, bioreactors and technologies cannot merely be scaled up but will also require localization to regional variations in feedstock, temperature, humidity, and sun exposure, among other factors. Such alignment can only be achieved by integrating substantive transdisciplinary collaboration and exchange right from the development stage. Collaboration, however, must extend beyond design and development. For example, collaboration will be required in overcoming roadblocks to change. The primary hindrance is one of economics: how will the costs of implementing new waste and recycling systems be distributed? Are these costs to be borne by taxpayers and the state, plastic industry players, consumer goods' companies, retailers, consumers, or recyclers themselves? This is a question that already plagues plastic control policies (Pathak and Nichter, 2019). Although more salient in low- and middle-income settings, it also presents a challenge for high-income countries. At its core, this question is about which stakeholders are to be held accountable—and to what degree—for plastic wastes. Furthermore, entrenched systems of plastic production, materials recovery, recycling, and disposal, whether formal or informal, bring with them stakeholders invested in the continuation of these systems (Pathak, 2022). Without buy-in from a significant proportion of stakeholders, implementation will fail. Here, the role of social scientists in developing policies that minimize distributional consequences, incentivize uptake, and promote social justice seems obvious. Yet the natural and technical sciences are essential to fine-tuning technologies and solutions such that they leverage existing infrastructures. Transdisciplinary exchanges will also be crucial to behavioural interventions and eco-literacy campaigns to build awareness and change social norms toward practices of plastic disposal suited to the new technologies and systems. Such campaigns will have to account for constraints faced by individuals, households, and communities, taking care not to reduce non-compliance to an issue of behaviour or choice alone (Shove, 2010). Moreover, such campaigns will be needed to overcome public resistance and misinformation. Finally, technological innovations can have unintended real-world consequences or can raise unforeseen concerns (such as when energy efficiency leads to increased consumption), and collaborative assessment efforts will be needed to monitor such effects and tackle them.

Even when effectively harnessed, scaled up, and translated to divergent real-world contexts, innovations in recycling technologies will address only the end stage of the plastic life cycle, revolving around plastic waste and disposal. Unless such degradation is combined with a reduction in production of virgin polymers, it cannot address issues of a continued dependence upon a carbon economy. Moreover, irrespective of the efficiency of plastic recycling, these processes cannot tackle other aspects of plastic-related pollution and contamination that proceed apace, such as the release of toxicants during plastic manufacturing (Abrahms-Kavunenko, 2021; Liboiron, 2021), the discharge of microplastics and nano-plastics during use, and the leaching into the soil, water, and food chain of endocrine disrupting chemicals that are used as polymer additives (Liboiron, 2016; Meeker et al., 2009). Tackling the harms of these other stages of the plastic life cycle too will require multi-scalar transdisciplinary interventions that centre issues not just of environmental but also social justice (summarized in Fig. 4). This need for transdisciplinary may seem obvious. It is also a tall order—difficult to implement and with many avenues of exploration. How, then, should we prioritize use of resources?

6. A call for transdisciplinary pragmatic melioration

Environmental crises at the scale where harm is caused by the very technologies and materials that we rely on can lead to either a sense of helplessness and cynical resignation or a desperate faith in salvation through techno-fixes. We make the call for a different stance, one of a transdisciplinary pragmatic approach revolving around harm reduction. Extending Pathak and Nichter's concept of pragmatic melioration (Pathak and Nichter, 2023), we call this stance ***transdisciplinary pragmatic melioration***. Pragmatic melioration draws from the work of the moral philosophers John Dewey and William James and envisions a middle path between an optimism that sees the world as automatically headed toward progress and a pessimism that views it as irrevocably doomed. It expresses a belief that the world can be improved and made more inclusive through human action (Liszka, 2022). This stance draws from public health models of harm reduction. Such models, developed to address addiction and dependence, recognize abstinence as an ideal but 1) accept alternatives while working toward that ideal, 2) emphasize a "bottom-up" approach (based on concerns from affected individuals and communities), and 3) promote low-threshold access to services (providing services based on real-world constraints) (Marlatt, 1996; Nichter, 2003). Applying this model to our contemporary plastic dependence would mean acknowledging that we cannot yet eliminate plastics, taking into consideration local constraints and concerns, and em-

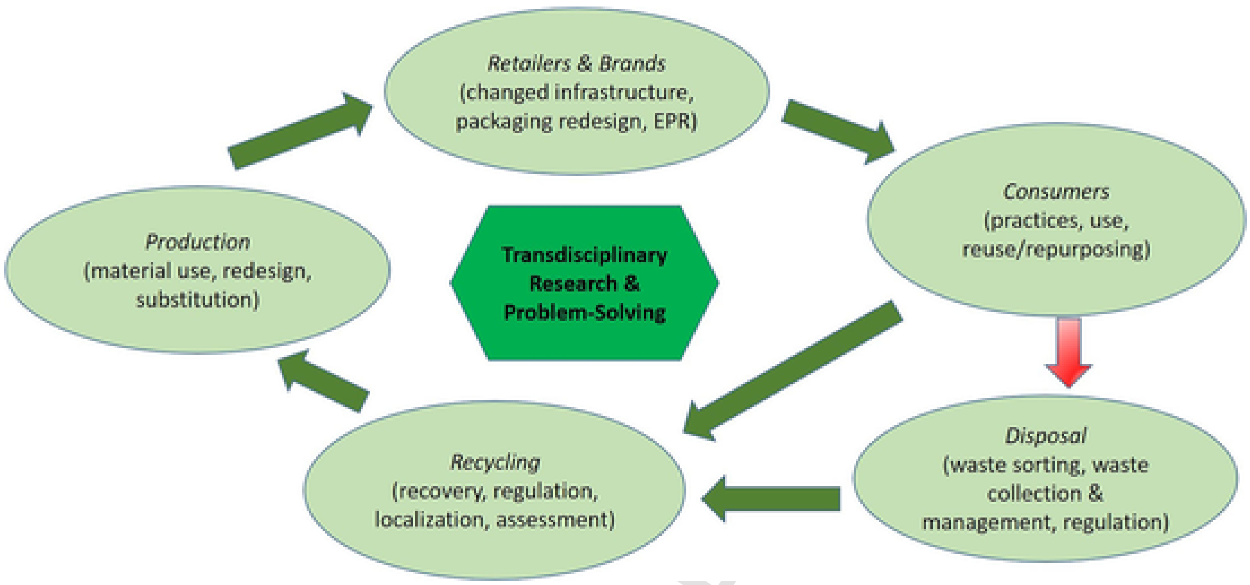

Fig. 4. A transdisciplinary approach for interventions across the plastic life cycle. The red arrow highlights major challenges in the sorting, collection and management of plastic waste.

phasizing local capacity-building and alternatives for safer, more sustainable plastic use, disposal, and recycling.

We advocate pragmatic melioration with a *transdisciplinary* emphasis on plastic stewardship and continually reducing plastics' most pernicious harms. For example, given the current state of recycling technologies and waste management challenges that we have reviewed earlier, such a stance would recommend prioritizing research and interventions toward shifting packaging away from plastics that are difficult to recycle (in socioeconomic as well as material terms) toward packaging with recyclable plastics such as PET. In terms of the larger plastic life cycle, this will require foundational studies to identify local and global sources of harm, not just in terms of human health and environmental justice but also in terms of social justice.

The Pareto principle states that 80 % of outcomes can be attributed to 20 % of sources. As a heuristic, it speaks to how a relative minority of inputs can affect a majority of outputs and suggests action targeted toward that critical minority. Prioritizing action in accordance with this insight, transdisciplinary teams will have to work to design localized interventions and policies that target the types of plastics and the plastic life cycle that are linked to maximal harm, especially for the most vulnerable and marginalized. For example, interventions—such as policies, community-based engagement for enhanced waste collection, technologies to produce alternatives, and design for reuse and easy waste collection—could target Styrofoam (which often escapes waste collection efforts as a result of its light weight and breakability, produces hazardous and combustible styrene gas when openly burned, and is currently not recycled) or small sachets (which are ubiquitous in the Global South, not recycled, and often end up as litter or openly burned). Sustained transdisciplinary conversations would allow such interventions to work in tandem to increase synergistic and cumulative effects. Periodic reassessments can then aid the continual targeting and shrinking of harms as we work toward plastic control. Overall, we believe that transdisciplinary pragmatic melioration can be leveraged as a way out of not just our plastic predicament, but it can also provide a model for tackling other environmental challenges and developing socially and ecologically sustainable policies.

Author contributions

All authors discussed the topics addressed in this paper, contributed equally to the writing, commented on the manuscript at all stages, and agreed on the final text. Fig. 2 was produced by D.E.O. and Fig. 3 was produced by G.S.P. and D.E.O. Fig. 3 is reproduced from Danso et al. (2019) with permission under the terms of the Creative Commons Attribution 4.0 International license. The Graphical Abstract was created with Biorender.com.

CRediT authorship contribution statement

D.E.O., M.H., and G.S.P. all contributed to conceptualization, writing – original draft and writing – review & editing. No funding acquisition, project administration or supervision was involved in this work.

Declaration of competing interest

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

Data availability

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

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