Untangling the chemical complexity of plastics to improve life cycle outcomes

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Abstract

A diversity of chemicals are intentionally added to plastics to enhance their properties and aid in manufacture. Yet, the accumulated chemical composition of these materials is essentially unknown even to those within the supply chain, let alone to consumers or recyclers. Recent legislated and voluntary commitments to increase recycled content in plastic products highlight the practical challenges wrought by these chemical mixtures, amid growing public concern about the impacts of plastic-associated chemicals on environmental and human health. In this Perspective, we offer guidance for plastics manufacturers to collaborate across sectors and critically assess their use of added chemicals. The ultimate goal is to use fewer and better additives to promote a circular plastics economy with minimal risk to humans and the environment.

[H1] Introduction

The "global plastics problem" is no longer simply defined by plastic waste polluting the environment—whether large, identifiable trash or invisible microplastics and nanoplastics—and its impacts on human and environmental health. Nor is it solely concerned with the high-molecular-weight synthetic polymers (resins) utilized in all commercial sectors and by essentially every person on the planet every single day. Scientific and public attention has highlighted the complex chemical composition of materials classified as plastics[1–3] and the risks associated with exposure to the voluminous, diverse, and largely unknown suite of plastic-chemical formulations in products manufactured, used, and disposed today[4–7].

A 2021 study[2] identified, from 63 scientific, regulatory and industrial sources, more than 10,000 substances with Chemical Abstracts Service Registry Numbers (CASRNs) that may be intentionally added to plastics. These substances include monomers and catalysts added during synthesis, and additives and processing aids included downstream, and their diversity is partly borne from the diversity of ways plastics are used in products spanning all manufacturing sectors. The study's analysis required a complex machine-processing approach to identify, assemble, and interpret poorly accessible data that are inconsistently and incompletely reported. Each substance (CASRN) was assigned a "level of potential concern"—low, medium, high, or unknown—based on previously established hazard criteria (most from European Union Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and other EU-based regulations) and the sparse information about global production volumes. 24% of these substances were found to be of medium or high potential concern because of their intrinsic hazard (toxicity), of which half elicited a high level of concern because of high production volumes (> 1,000 tonnes per year). More than a third of the identified chemicals (39%) lacked information in the databases used; thus, the level of concern for a substantial fraction of plastic-associated chemicals is unknown.

Management of plastic-associated chemicals is not simply a matter of preventing pollution and choosing safer alternatives for their manufacture and use. Use (and overuse) of these chemicals can hinder efforts to advance a circular plastics economy, and address growing amounts of plastic waste, through recycling. The suite of proposed actions to improve material circularity includes setting targets for increased use of post-consumer recycled content in plastic products. Some targets have been legislated, such as the United Kingdom's Plastic Packaging Tax (30% recycled content in all plastic packaging) or California's 2020 AB 793 law (15% recycled content in plastic beverage bottles, increasing to 50% by 2030). Many corporations and brand owners have voluntarily pledged to increase post-consumer recycled content in plastic packaging (for example, signatories of the Ellen MacArthur Foundation Global Commitment and the associated global Plastics Pact Network). These targets have now highlighted the deficiencies of even the most optimised mechanical recycling systems, such as those in the European Union, while sparking interest and investment in thermal or chemical decomposition processes (inconsistently and confusingly referred to as "chemical", "advanced", or "molecular" recycling[8]). Each mechanical and chemical recycling process has different tolerances for chemical contaminants in feedstock (waste plastics), which can be technically difficult to overcome[9]. Even when plastics are successfully reprocessed, concerns about chemical contamination of the recyclate arise, especially in food contact applications where there is evidence of contamination and chemical migration from recycled plastics[10,11].

There is a compelling business and environmental case for improving the quality of waste streams, because the market value of a recycled resin is largely determined by the purity of its waste feedstock[12]. This economic potential can incentivize innovation in recycling technologies and promote investment in infrastructure that would drive up demand for waste plastics. As this demand grows, so will the incentive to recover rather than discard plastic products. The environmental impact could resemble that of container deposit schemes, in which redemption of a deposit paid at time of purchase incentivizes capture of beverage containers in the recycling supply chain, simultaneously discouraging their loss to the environment[13,14].

In this Perspective, we offer guidance for the plastics manufacturer (resin producer, compounder, converter) to make informed decisions about selecting and using additives for product design and processing. The tripartite goal of these decisions is to retain product benefits while optimizing the material for reprocessing and minimizing health risks. This advice is informed by our shared knowledge, diverse research experience, and substantial stakeholder engagement from a collective expertise spanning environmental science, plastics engineering, polymer chemistry, and toxicology. Our mission is to pose seemingly simple questions that are not necessarily simple to answer, spurring the necessary deep dives by practitioners across a complex supply chain in collaboration with cross-sector partners.

[H1] Chemicals in plastics manufacture

Chemical additives and processing agents have been used to design and manufacture plastics since the start of synthetic polymer research and development[15]. Their current use is built on extensive and painstaking work over the past century linking polymer formulation to plastics performance[16,17], and this body of knowledge should inform efforts to overcome the downstream challenges associated with polymeric products.

Additives give polymers the seemingly limitless versatility they are known for, by softening (plasticizers) or stiffening (fillers, which may also be used to reduce cost), providing aesthetic function (colorants and dyes), and improving safety (flame retardants), durability (UV stabilizers) and processability (stabilizers for melt processing or mechanically recycled resins)[18–20] [TABLE 1]. Oxo-degradable plastics often contain pro-oxidant additives designed to promote oxidative breakdown[21], although the safety and efficacy of these additives have been refuted in scientific studies[22,23]; trade and environmental groups do not support their use (Association of Plastics Recyclers Position Statement on Degradable Additives, Ellen MacArthur Foundation Statement on Oxo-Degradable Plastic Packaging, World Wildlife Fund Position Statement on Biobased and Biodegradable Plastic), and the European Union prohibits it (Directive 2019/904 of the European Parliament). Other chemicals associated with plastics are not additives with an intended function, but instead remnants from processing, such as residual monomers from incomplete polymerisation, embedded residual catalysts from synthesis, or surface mold release agents from injection molding.

Chemicals may be intentionally added at each stage of plastics manufacture [FIG. 1]. First, resin manufacturers synthesize the polymer, introducing monomers and catalysts. Compounding companies, or formulators, then incorporate various additives to give the resin specific properties or functions. Finally, converters can process, combine, or modify the compounded materials into a specific form or product ready for production into a final product or package. Most additives are incorporated at the compounding stage by companies who produce neither the primary polymer resin nor the final goods. These additives may be added individually by specialised compounding processes to enable new functions or aid processing, or as proprietary “masterbatch” blends of concentrated additives prepared by a third party[15]. Finally, additives can be included—purposefully or otherwise—by converters during material forming (such as blowing aids during extrusion, or mould release agents during shaping), finishing (such as adding décor to the product surface) or assembly[18]. The supply chain for a particular plastic product may involve multiple compounders or converters, with similar and/or different additives added at each stage. The effective number and concentration of additives can vary greatly depending on the application.

For illustrative purposes only, as there is no exemplar, we consider the manufacture of a hypothetical, non-food-contact, multilayer film packaging product. A low-density polyethylene (LDPE) manufacturer adds oxidative stabilizers during the synthesis of a LDPE resin, for sale to a material compounder. The compounder melts and mixes the LDPE pellets with a third-party masterbatch containing UV stabilizer and more oxidative stabilizer, along with titanium dioxide to color the resin white. The white LDPE is sold to a sheet manufacturer, who adds processing aids to form rolls of LDPE sheet to sell to a package manufacturer, who then laminates the sheet with polyethylene terephthalate (PET), adhesives, and inks to make a packaging film. The multilayer film is sold to a manufacturer who fills, seals, and labels the product package, adding more adhesives, inks, and paper. The final "polyethylene" package found on store shelves has been formulated and manufactured by four independent processors (not including the resin and masterbatch manufacturers), who have added unknown numbers, amounts, and types of additives to create the branded end-product on the market.

It is important to note that if the package had been formulated for food-contact applications, regulatory standards would apply, limiting allowable additives and requiring more transparency into the chemical content of the product. Despite these standards, chemicals have been detected to migrate from plastic packaging into food[10], including chemicals not previously known to be used in food-contact materials[11]. Biomedical grade plastics are also strictly regulated, with compliant products required to meet rigid healthcare industry standards (for example, USP Class VI, USP661.1, ISO10993, BS5452) and be traceable along the supply chain without revealing sensitive business information. Other than for food-contact and biomedical applications, few such standards or chemical migration studies exist for consumer plastics, and thus their composition and potential for contamination is unknown.

These chemically-enhanced plastic materials are marketed according to their beneficial properties, without disclosing ingredient lists to protect perceived confidential business information or trade secrets. Thus, little to no information about chemical composition of a material is shared down the supply chain, resulting in potentially unnecessary duplicative additions (for example, see oxidative stabilizers or plasticizers in FIG. 1) and immense variation in both the type and amount of chemical compounds in final product formulations. Regulations for food contact applications may require further information sharing, but provide little ability to assess information integrity and no responsibility to share it with end users. Consequently, chemical formulations are unknown even to the final product manufacturer, let alone to the retailer or consumer.

Along the entire life cycle, plastics also accumulate non-intentionally added substances (NIAS), including residuals and byproducts from each manufacturing step, and contaminants acquired during use or upon environmental exposure. Although environmental contaminants such as polychlorinated biphenyls and chlorinated pesticides are well known to adsorb to plastics[24,25], the full suite of NIAS actually present in plastics is not completely understood. Identifying the full complement of acquired chemical constituents is non-trivial, requiring sophisticated non-targeted analyses that can suggest possible chemical structures but cannot confirm them without the synthesis of analytical standards[26,27]. In addition, species in such chemical mixtures can cross-react, which could alter their intended function or produce secondary by-products with unknown properties[28].

[H1] Health impacts of added chemicals

Many of the chemicals intentionally (and non-intentionally) added to and accumulated in plastics during their manufacture are known to be toxic and can potentially impact the health of humans and the environment[1,2,29–31]. Several commonly used additives, including plasticizers such as phthalates, and flame retardants such as polybrominated diphenyl ethers, are harmful to humans and wildlife[6,32,33]. Because most additives and NIAS are not chemically bound to the polymer, they can migrate from plastics through contact with other substances, such as from food packaging to food[34], and from plastic debris into the aquatic[35] or terrestrial environment or to biota that encounter it[36,37]. Adverse effects of plastic leachates have been shown in a variety of systems, including *in vitro* (cell-based bioassays) and *in vivo* (animals and plants)[4,35,38–40]. The leaching mechanisms are complex and are influenced by the chemical, the polymer, the geometry of the plastic, and environmental conditions[24,41].

In addition to posing hazards upon release from plastics, hazardous chemicals may impact health at earlier stages of the chemical and plastics life cycles, including synthesis, transport, and production[6]. Even chemicals with low intrinsic hazard may be transformed by environmental conditions (such as sunlight[42] or pyrolysis[43]) into more toxic products[36]. Moreover, even when individual chemicals are present below levels of concern, their complex interactions within chemical mixtures can induce toxicity[44–48], as shown for some endocrine disruptors[47,49].

Additive loadings are typically calculated in weight% at the point of addition, ranging from < 1% to > 50%[35], but this value does not account for accumulation over multiple manufacturing steps and recycling cycles. Given the increase in recycling in many countries, particularly in Europe, the unknown cumulative concentrations are a concern. Quantifying additive concentrations is even more complex when considering the relative solubilities and diffusivities of different additives, sorbates, and small molecule byproducts in the polymer matrix. Together, this poses a metrology challenge, which makes it difficult, if not impossible, to use established methods to quantify the potential risk from an identified hazard. As it is dangerous to discount uncertain risks, the focus of our discussion is on the potential hazards.

[H1] Effects of additives on recyclate quality

After use, plastic waste collected for recycling is frequently commingled with other material types, all of which may be contaminated by food or other product residues. Formal collection systems may or may not exist depending on the region, and where there is systematic recycling aggregation it may be municipal single-stream, deposit and redemption, or post-industrial and specialty scrap collection. Waste management material recovery facilities are tasked with separating materials by base resin (typically PET, high density polyethylene (HDPE), and polypropylene (PP)) and form factor (for example, rigid container, food and beverage cartons) to produce bales with minimal contamination. They sort using automated sorting technologies (such as infrared signature, image recognition, or embedded tags) or through manual labor based on product type (for example, PET drink bottles, HDPE milk jugs, PP yogurt pots), but cannot typically distinguish additive composition beyond, in some instances, an item's color (for example, natural (uncolored) vs. colored HDPE containers). In some cases, additives such as carbon black[50] may even obscure the infrared signatures used in automated sorting.

Plastic reprocessors who purchase the bales must ultimately contend with the full suite of unknown additives, as well as NIAS and environmental contaminants that have accumulated along the product life cycle. Even if additives can be identified, it is not trivial to remove them during mechanical processing. For example, solid fillers, such as glass and talc, can only be removed by melt filtration, which is both costly and typically unable to remove everything. Mixtures of colorants that can't be removed result in aesthetically compromised brown and gray recyclate. Along the supply chain of PVC, phthalate plasticizers may be added in fractions from a few percent to 50% by weight to soften the material to a suitable stiffness. When this PVC is later recycled, adjusting the recyclate to a new desired level of stiffness is challenging, especially if plasticizer must be removed to rigidify the material for a secondary application.

Even in the best-case scenario—reprocessing of a single product type, such as PET beverage bottles or natural HDPE milk jugs—mechanical recyclers can encounter substantial variation in chemical composition[51,52], unless international product manufacturers have already agreed to a standard composition. (One such example is the standardization of HDPE formulations in British milk jugs, discussed in the next section.) The variability in feedstock composition is a consequence of decisions made at many points in a product's manufacturing history as well as additive loss and chemical sorption during use[20]. Reprocessors incorporate even more additives to mitigate this variability, provide quality assurance, and prevent mechanical failure. They also use additives to improve compatibility in heterogeneous polymer mixtures. Still, recyclate that deviates in quality owing to feedstock inconsistencies is often unacceptable for certain uses and may be suited only for applications of lower performance, aesthetic, or value.

Although currently it is rare for a plastic to have been recycled more than once—owing to both inefficient waste collection or sorting systems and the diversion of feedstock to different sectors (for example, HDPE milk jugs reprocessed into laundry bottles, or PET bottles into textile fibres)—growing demand for post-consumer feedstock could ultimately increase the amount and variability of additive content with each reprocessing cycle. This accumulation may also include toxic compounds that were initially added in only small quantities to meet food safety standards[53]. Knowing the chemical composition of each batch would improve recycling outcomes, especially in closed-loop systems such as bottle-to-bottle recycling[10] or with emerging sorting technologies enabled by artificial intelligence (AI) or tagging[54,55].

An emergent set of end-of-life technologies that use either selective or non-selective chemical reactions to break down materials, loosely referred to here as "chemical recycling",[8,18,56] is potentially complementary to mechanical recycling. The sustainability of these strategies is a topic of ongoing debate and comparative analysis.[57] Chemical recycling methods, which include solvent-based cleaning, depolymerization, and pyrolysis, have the potential to separate or degrade complex additives from their constituent parts. However, additive contaminants affect the efficiencies of these methods by interfering with catalytic reactions and separation stages[58,59]. As alternatives to mechanical recycling are sought, it is important to also understand the influence of intentionally added compounds on chemical recycling processes to ensure consistent, safe, and efficient operation of plants. To date, little information on formulation-reaction interference is available to guide recyclers in this nascent field.

The multilayer LDPE-based film example discussed earlier would likely never enter the reprocessing stream depicted in FIG. 1. Most material recovery facilities remove plastic films for disposal (by landfill or incineration), and even if the film were recovered, the multilayer construction would render it a contaminant in LDPE film recycling streams. In fact, few plastic products—mainly rigid single-resin containers and some single-layer films—are ultimately baled for sale to reprocessors. Given the link between purity and quality in secondary manufacturing, reprocessors would benefit from the ability to detect and mitigate chemical contamination that compromises these streams.

[H1] What next for the plastics manufacturer?

Some plastics manufacturers are well positioned as critical decision makers in the central supply chain—in particular those involved in multiple steps of the supply chain and that have strong information management systems. This standing enables them to drive necessary change, while retaining competitiveness and innovation, to address the environmental and lifecycle concerns presented by intentionally added chemicals in plastics. These changes include reducing the complexity and eliminating unnecessary use of plastic-associated chemicals; increasing the consistency and compatibility of chemical formulations across materials and products; and ensuring that formulation decisions are informed by function, chemical migration and interaction behaviors, and the potential impact on human and environmental health [BOX 1]. By making these changes, plastics manufacturers would optimize material quality both during use and in reprocessing, while minimizing potential harm.

By critically assessing the additive content in their products, companies can potentially lower costs by reducing additive use, or by achieving economies of scale by using consistent formulations across materials or product types. For companies mandated or voluntarily pledging to increase post-consumer recycled content in their products, consistency in primary feedstock formulations will ensure that there is enough such material to procure later for recycling, bringing supply chain security. The standardization of British milk jugs is an excellent example: when cross-sector agreement on HDPE formulation permitted the closed-loop collection and recycling of plastic milk bottles from household waste, the homogeneity of the feedstock increased the target recycled content from 30 to 50%[60]. This change spurred design changes in the milk jugs to further improve recycling outcomes, including making the caps and closures without pigments. There is growing demand for international and federal regulations to achieve similar goals, especially in light of current international negotiations on a treaty aimed at addressing global plastic pollution[5,31]. Companies who choose to address these questions in the short term will not only face less regulatory pressure down the road, but may also win early public support and gain a strong consumer brand image.

These outcomes require a step change in industrial collaboration across the supply chain, especially for small or mid-size manufacturers who lack the capacity and resources of major corporations. Additional partnerships with academia, government agencies, and non-governmental organizations engaged in plastics research would instill a much deeper understanding of the impact of additives and other chemicals on recycling outcomes and the environment. A transparent, open database and decision tool that extends green chemistry[61,62] and design-for-recycling principles would empower open collaboration from resin production through reprocessing, without compromising competitiveness in the marketplace. Such tools are emerging for the packaging sector, with the UK industry-led Open 3P Data Standard, which aids in data curation for both regulatory compliance and improved decision-making, and the Design for Recycling Guidance by the Association of Plastic Recyclers and RecyClass, a partnership between a U.S.-based and Europe-based group, to align and enhance their design guidelines for plastic packaging to promote recycling.

Although design-for-recycling efforts have been ongoing for many years, they often focus on the physical components of a package rather than its chemical composition.

Neglecting additive content across manufacturers, even among those who make products with similar components, diminishes recycling outcomes. Advanced sorting enabled by chemical composition disclosure—such as sorting by RFID[54] or molecular tag[55]—could be a key method in the future, enabling sorting of products with standardized compositions by product type[63] or excluding products with incompatible additive content. Finally, extending these tools to other major sectors, such as electronics, textiles, and construction, could sizably improve end-of-life outcomes for a larger proportion of plastic products.

[H2] What additives are present

We outline a process that plastics manufacturers can follow to make informed decisions about adding chemicals to plastics, in order to improve life cycle outcomes from synthesis to use to reprocessing. Manufacturers should first examine every upstream stage in the existing supply chain, starting with raw plastic resins (whether from virgin or recycled feedstock), to determine the specific composition of the plastic at each stage—rather than only the generic functions of the additives [BOX 1, #1]. For example, a "UV stabilizer" added to a resin could refer to any of numerous chemicals, each of which may interact differently with other additives down the supply chain or compromise recycling.

The currently used "forensic approach" to determining the chemical composition of products by back-end laboratory analysis is inefficient and incomplete, and falls short of the transparency required for full lifecycle chemicals management. Such information could be provided via voluntary or regulation-driven labeling or tagging of formulations. For example, AccuStandard, Inc. publishes a Plastic Additive Standards Guide that catalogues the chemical composition of trade name chemical additives used in several plastic product categories (such as food packaging, toys, consumer devices, pharmaceutical packaging), but omits details such as molecular weights, specific amounts and formulation process to protect company information security. Improved information flow can be enabled by open-source tools that allow for the sharing of different levels of information with supply chain partners, and trade body agreements requiring key information about additive selection to be shared on material data sheets.

[H2] What additives are necessary

Once manufacturers know better the chemical composition of purchased resin or compounded materials, they can critically assess whether their product formulation can be simplified by omitting functionally redundant or otherwise unnecessary additives, or those that might be cross-reactive or inappropriate for a particular recycling technology.

[BOX 1, #2]. For example, if manufacturers apply the "essential-use" approach—either voluntarily or as a result of regulation— hazardous chemicals would be used only when their function is absolutely necessary and no suitable alternatives are available[64]. The addition of unnecessary chemicals—such as those that provide functions to products not requiring them or that serve only aesthetic purposes—not only violates green chemistry principles, but can also compromise recyclability. For example, the dye used in the green Sprite bottle manufactured by the Coca-Cola Company was an unacceptable contaminant in the clear PET recycling stream, lowering the intrinsic value of these high-collection, food-grade bottles. In 2022, the company changed the iconic, designed-for-marketing green bottle to a clear bottle, consistent with the vast majority of other PET drink bottles, and in 2024 trialed replacing paper or plastic film labels with embossed and laser-engraved information. These changes promote higher value bottle-to-bottle recycling, increasing available post-consumer recycled feedstock to meet recycled content goals.

[H2] How additives behave

A wide range of unintended consequences result from a poor understanding of additive behavior throughout the product lifecycle, including leaching into products and ecosystems, adverse interactions between chemicals, and interference during mechanical or chemical recycling [BOX 1, #3]. Because recycled PET (rPET) is used extensively in the EU, the contamination of PET streams has been examined in more detail than that of other resins[65]. Inconsistent sorting, variations in additives in PET bottles compared to trays, and metrology challenges for both small molecule and polymeric additives highlight the difficulty in tracking problematic or hazardous chemicals. While relationships between additives and processing conditions and performance are emerging for PET[66] (RecyClass Testing Methods), many other complex interrelationships demand collaborative research efforts. For example, when PP contaminates HDPE recycling streams, compatibilizers must be added to mitigate the damage to recyclate properties; however, it is largely unknown what composition and structure of compatibilizer is needed to confer ideal properties to the HDPE recyclate for a given application[67]. Although it is recognized that resins should have matching melt-flow rates to combine their waste streams, this parameter is a crude measure of processing behavior. Unexpected flow behavior and performance can result even with matched rates, necessitating further additive use[68].

Building upon efforts by the Organisation for Economic Co-operation and Development to guide chemical considerations in plastic product design[69], metrology agencies such as National Institute of Standards and Technology (NIST) and standards organizations such as International Organization for Standardization (ISO) could devise methodologies to identify additives in recycled feedstocks that are straightforward enough to be applied broadly by the diverse communities that would use them. The development of these tests is, of course, not trivial and requires appropriate financial and sector support. Bodies such as NIST and ISO are suited to cooperate and engage in the pre-competitive work needed to boost global supply chain security and trust.

Major strides can also be made through industry collaboration. For example, PET bottles in the UK are predominantly recycled content from bottle-to-bottle recycling. This is enabled by not only the segregation of bottle stock across homes and businesses, but also collaboration among major beverage manufacturers to use near-identical feedstocks as well as adhesives and labels that are readily removed in caustic washing. Recycled bottles that are up to 100% rPET indeed show visual signs of the mechanical recycling process (grey or yellow haze), yet this colour has become a mark of circularity and a purchasing preference for consumers. This sector-based improvement relies on all stakeholders understanding the deleterious impacts of waste stream contamination and demonstrates positive consumer perceptions of recycled content.

[H2] How safe are additives

Beyond existing regulatory requirements for particular product categories, a manufacturer should select additives that fulfill essential functions while minimizing any resulting environmental and human health impacts [BOX 1, #4]. Adverse impacts are often determined using risk-based approaches that take into account both intrinsic hazards and potential for exposure. Given the vast numbers of chemicals that require assessment, the difficulties of assessing exposure, and the ability of some chemicals to cause toxicity at very low doses, some researchers have argued for a move away from risk-based approaches towards those based solely on hazard properties[70–72], regardless of exposure level. While discussions continue about whether risk- or hazard-based models are most effective[27,70–72], hazard assessment remains a critical element of any effort to select safe additives. Nevertheless, estimates of potentially high exposure, when available, may still be useful to prioritize chemicals for testing.

A large number of chemical databases—from a variety of sources—provide complementary information on chemical hazards, including a variety of toxicological endpoints of concern [BOX 2]. For chemicals not yet represented in the existing databases, quantitative structure-activity relationships (QSARs)[73] or a “read-across” framework[74] can be used to predict their potential hazard. Application of these approaches is likely to be facilitated by emerging AI methods[75,76]. When computational predictions are insufficient, a set of rapid screening tests [BOX 2] could be used to quantify the different types of potential biological hazards posed by a particular additive or polymer formulation. Such a toxicology profile could also narrow the number of acceptable alternatives and thus guide firms in their selection of preferred additives.

The task becomes more challenging when trying to avoid additives that might undergo biological or environmental transformations to more toxic products[42]. Scant information is currently available to inform such decisions. Another limitation of current databases is that they generally deal only with effects of individual chemicals; assessing the risk of chemical mixtures remains a challenge[45,46,48]. Although complete answers to questions about chemical behavior and risk may not be possible at present, due diligence carried out across the supply chain will reveal the most pressing knowledge gaps and barriers to change. Open research collaborations between trusted academic and industry partners[77] could accelerate the incorporation of chemical hazard assessment in material design, supporting due diligence efforts and the development of standards. These efforts could motivate sector-wide change, and also feed into local, national, and global policy discussions (that is, international treaty negotiations) to promote wider propagation of best practice.

The guiding questions for plastics manufacturers [BOX 1] encourage aspirational thinking toward designing a safe and circular plastics lifecycle. As highlighted in Question 1, the disclosure of formulation components—of the additives being used at each stage of the manufacturing process—is essential to unlocking more sustainable practices. This disclosure can promote better supply chain collaboration by reducing duplicative additives; inform procurement, helping to avoid additives of concern for specific use cases or those that may conflict with each other; and ensure that the right additives are used for necessary functions. These steps will promote economic and environmental sustainability, lowering both costs and footprint. There is a perception that this disclosure could undermine competitiveness; however, substantial—if somewhat inadequate—disclosure already occurs for food-contact and biomedical materials without undercutting commercial outcomes. We envisage a future where material formulation components are presented similarly to ingredient labels on our foodstuffs: indicators of what is in there and in what relative quantities, while avoiding the disclosure of key commercial variables such as formulation methodology or exact composition when safe to do so [FIG. 2]. It is easy to see what goes into a bottle of ketchup from the label, but difficult to recreate the secret sauce.

Coupling this knowledge to more closed-loop segregation of feedstocks is key to preserving quality of recyclate, especially in mechanical recycling and likely also in emerging chemical recycling technologies. Properties of recyclate improve when matching the starting melt-flow rates of products, with bottle-to-bottle, tray-to-tray and film-to-film pathways preferred. Sector-wide collaboration to use fixed additive sets—just as with fixed melt-flow rate ranges—can dramatically decrease the complexity of both known and NIAS contaminants on recycling, consequently improving outcomes and reducing risks.

[H1] Outlook

Plastics manufacturers are uniquely positioned to drive necessary improvements in life cycle outcomes of their products by using only the number and amount of intentionally added chemicals deemed necessary, and by choosing chemicals that optimize material performance while minimizing chemical loss, reactivity, and harm. Only when these goals are met can the circular economy of plastics be achieved. The approach we describe here is complementary to calls for materials scientists to consider end-of-life management and environmental persistence in material and product design[87,88] to reduce the impacts of plastic pollution. Businesses that proactively make such improvements will be better prepared to respond to increasing calls for international governance and regulation on plastics production[3].

The myriad benefits plastics offer to society have arisen from human ingenuity, but a failure to imagine the consequences of complex product development has led to the modern-day crisis in plastics waste management and toxicity. We argue that the solutions will emerge from the human capacity to evolve and invent products and systems, with cooperation across material and product supply chains locally and globally, and collaboration across industry and non-industry. We offer a process for critically evaluating the status quo that firms and organizations can incorporate into their present decision-making strategies, with the goal of a safer and more sustainable plastics industry. Collaboration and transparency reduce risks, improve sustainability, and decrease economic costs. Industry-led progress towards these goals would not only bring favorable business and environmental outcomes, but could also improve public attitudes at the intersection of plastic materials and human and environmental health.

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Related links

Ellen MacArthur Foundation Global Commitment: https://www.ellenmacarthurfoundation.org/global-commitment-2022/overview

Plastics Pact Network: https://www.ellenmacarthurfoundation.org/the-plastics-pact-network

Position Statement on Degradable Additives: https://plasticsrecycling.org/images/position_statements/APR-Position-Degradable-Additives.pdf

Statement on Oxo-Degradable Plastic Packaging: https://emf.thirdlight.com/link/kfivzcx91l81-86a71k/@/preview/1

Position Statement on Biobased and Biodegradable Plastic: https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/5tm1hfp3vz_WWF_Position_Biobased_and_Biodegradable_Plastic.pdf

Directive 2019/904 of the European Parliament: https://eur-lex.europa.eu/eli/dir/2019/904/oj

Open 3P: https://www.open3p.org/

Design for Recycling Guidance: https://recyclass.eu/news/apr-and-recyclass-work-to-align-design-for-recycling-guidance/

Plastic Additive Standards Guide: https://www.accustandard.com/media/assets/Plastic_Add_Guide2018.pdf

RecyClass Testing Methods: https://recyclass.eu/recyclability/test-methods/

Display items

Table 1: General classes of chemicals commonly used in plastics manufacturing.

Additives	Example Trade Names	Functions
Phenols, phosphites and their blends	Irganox®, Cyanox®	Antioxidants
Hindered amines	Tinuvin®	Light stabilizers
Phthalates, chlorinated paraffins, esters	Jayflex®, Santicizer®	Plasticizers
Fatty acid amides or esters, stearates	Accrochem®, Finostab®	Slip agents
Silicones, siloxanes	Tegostab®, Andisil®	Processing aids, blowing agents
Brominated diphenyl ethers, chlorinated aromatics, metal oxides, phosphates	Akrochem®, Saytex®, Disflamoll®	Flame retardants
Azodyes, titanium dioxide, other metals	Ti-pure®, Vynamon®, Stan-Tone®	Colorants and pigments
Calcium carbonate, glass fiber, carbon black, fumed silica	Omyacarb®, Black Pearls®, Advantex®	Fillers and reinforcements
Titanium catalysts, maleic anhydride grafted polymers, block copolymers	Kenrich®, Graftabond®	Compatibilizers and chain extenders
Metal stearates, metal carboxylates	Reverte®, Coraplast®	Pro-oxidants, pro-degradants

More comprehensive inventories on chemicals intentionally added to plastics can be found elsewhere[2,15,35,36,89].

Table 2. Resources for Evaluating Chemical Hazards

Database	Description	References
eChemPortal (OECD and ECHA)	Provides links to a variety of international databases with information on chemical properties, including chemical hazards and classifications according to GHS.	https://www.echemportal.org/echemportal
EU ECHA databases associated with regulations such as REACH, CLP, POP. [See also the International Uniform Chemical Information Database (IUCLID)]	Persistence, bioaccumulation, carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, specific target organ toxicity upon repeated exposure, and chronic aquatic toxicity.	Fantke *et al.* 2020[90] OECD 2023[91] https://echa.europa.eu
EU-ToxRisk	Data from a collection of *in vitro* tests using human cells and a zebrafish embryo toxicity assay.	Krebs *et al*., 2020[92] https://eu-toxrisk.eu
U.S. EPA ToxCast	700 high-throughput *in vitro* assays using human cells for multiple cell responses and signaling pathways.	Richard *et al*., 2016[93] https://www.epa.gov/comptox-tools/toxicity-forecasting-toxcast
U.S. EPA CompTox Chemistry Dashboard	Environmental fate and transport, *in vivo* toxicity, *in vitro* toxicity data.	Williams *et al*., 2017[94] https://www.epa.gov/comptox-tools
U.S. EPA ECOTOXicology Knowledgebase (ECOTOX)	Knowledgebase providing single chemical environmental toxicity data on aquatic and terrestrial species.	Olker *et al*., 2022[95] https://cfpub.epa.gov/ecotox/
International Agency for Research on Cancer (IARC) Lists	Chemicals that pose carcinogenic hazards to humans.	https://monographs.iarc.who.int/list-of-classifications/
Stockholm Convention on Persistent Organic Pollutants (POPs)	Lists of POPs targeted for elimination, restriction, or avoidance of unintentional production.	https://www.pops.int
Endocrine Disruption Exchange (TEDX) list	List of potential endocrine-disrupting compounds.	https://endocrinedisruption.org/interactive-tools/tedx-list-of-potential-endocrine-disruptors/search-the-tedx-list
Chemical Hazard Assessment Database (CHAD) of the U.S. Interstate	Links to GreenScreen lists of chemicals.	https://www.theic2.org https://www.greenscreenchemicals.org

Chemicals Clearinghouse (IC2)		
Massachusetts Toxics Use Reduction Act (TURA) list	All toxic or hazardous substances regulated under TURA and subject to reporting and planning requirements.	https://www.turi.org/Our_Work/Policy/TURA_List
California Department of Toxic Substances Control (DTSC) Authoritative Lists	Twenty-three authoritative chemical lists based on hazard traits (15), and potential exposure concerns (8).	https://dtsc.ca.gov/scp/authoritative-lists/
California Proposition 65 List	A list of chemicals that are known to cause cancer or birth defects or other reproductive harm.	https://oehha.ca.gov/proposition-65/proposition-65-list
U.S. Plastic Pact's Problematic and Unnecessary Materials List	A list of 11 problematic and unnecessary resins, components, and formats to be eliminated by 2025 in order to accelerate progress toward a circular economy for plastic packaging in the United States.	https://usplasticspact.org/problematic-materials/
ChemForward	Chemical hazard assessments including more than 21 human and environmental toxicology endpoints. Based on GHS.	https://www.chemforward.org/materialwise
Sixclasses (Green Science Policy Institute)	Focus on entire classes or groups of chemicals of concern.	https://www.sixclasses.org/
USEtox	A "scientific consensus model" for characterizing human and ecotoxicological impacts of chemicals; includes fate, exposure, and effect parameters.	https://www.usetox.org
PlastChem State of the Science on Plastic Chemicals	A compilation of information on known plastic chemicals and their hazards (report and database).	https://zenodo.org/records/10701706

Note: Examples of databases and other resources for evaluating chemical hazards. The reliability of data sources has not been verified by the authors, and inclusion does not imply endorsement. Some of the descriptions have been reproduced directly (or with slight modification) from the associated web sites. Many of these databases classify chemicals according to the Globally Harmonized System for the classification and labeling of chemicals (GHS)[83,96].

For more comprehensive and detailed lists of hazard data sources, please consult ref. [29] (Table S1), ref. [30] (Supplementary File 2); ref. [2] (Section S1.4, Table S5, Sheets S1 and S2 in Supporting Information S1), ref. [1] (Table S3), and ref. [85] (Supplemental files).

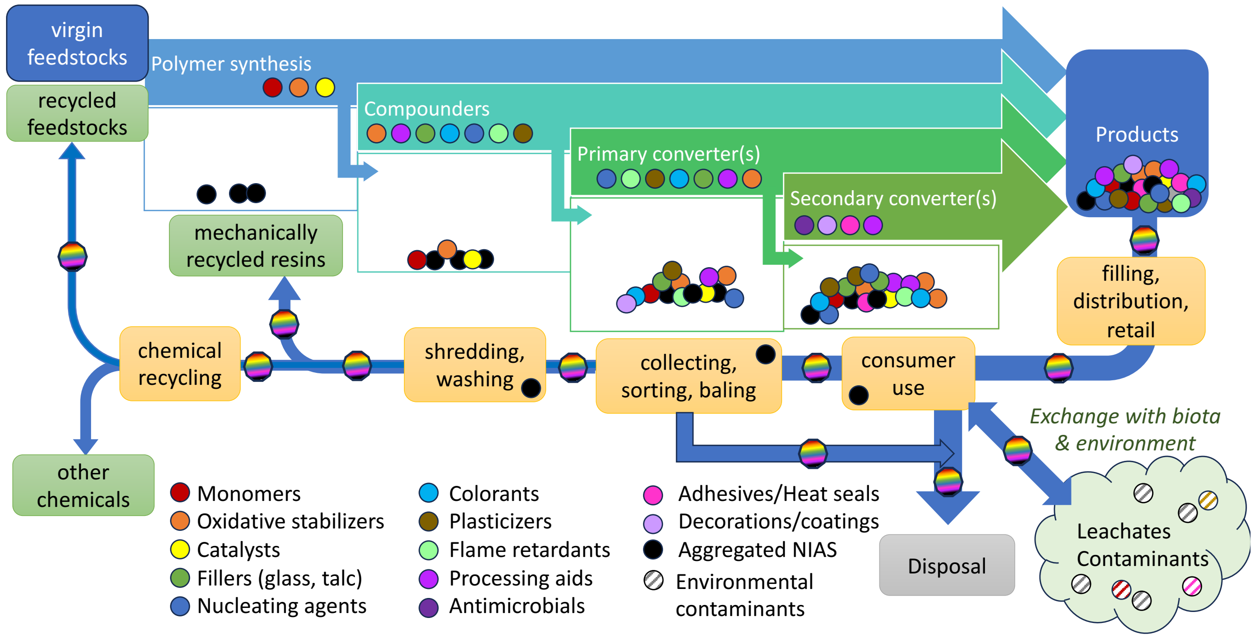

Figure 1. The life cycle of a plastic product. The life cycle of a plastic product, from manufacture to end-of-life, is defined by increasing, and largely unknown, chemical complexity. Colored circles indicate classes of chemicals intentionally added throughout the supply chain (top arrows and boxes), while black circles indicate non-intentionally added substances (NIAS). These chemicals may leach from the product during use or upon loss to the environment, posing potential health risks, and other contaminants (hatched circles) may be added. The increase in number and amount of ingredients in these chemically complex plastics directly impacts end-of-life recycling processes (multicolored symbols in bottom arrows) and the quality and market value of recycled resins and other chemical products.

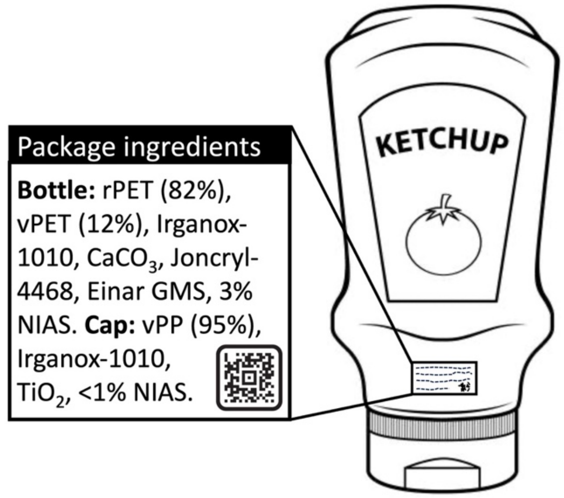

Figure 2. Conceptual package composition label of the future. Label disclosing plastic bottle composition to supply chain partners and, ideally, consumers. Composition details are not representative of real additives or bottle formulation.

Box 1: Guiding questions for plastics manufacturers

Reducing the chemical complexity of plastics by informed decision-making is essential. Together, the following questions guide plastics manufacturers to use fewer, less, and better additives:

1. What is actually in the plastic feedstock?

2. What additives are genuinely needed?

3. How do these additives move and interact through use and recycling?

4. Are these additives safe for human and environmental health?

Box 2: Assessing chemical hazard

Chemicals under consideration in plastics manufacture should be assessed for a broad range of hazard traits[64], including not only direct toxicity but also physical and chemical properties that may lead to adverse impacts on health or the environment, such as ozone depletion, climate effects, or interference with recycling. Chemical toxicity includes impacts on the health of both humans and wildlife. Toxic effects of concern typically include carcinogenicity, mutagenicity, target organ toxicity, reproductive and developmental effects, endocrine disruption, activation of toxicity pathways, toxicity to aquatic organisms, and other relevant endpoints.

A variety of data from both *in vivo* and *in vitro* assays are available for thousands of chemicals. Some of the data come from high-throughput *in vitro* screening tests carried out in the U.S. (ToxCast; Tox21; CompTox databases[78,79]) and Europe (EU-ToxRisk[80]). Although most assessments focus on toxicity, it has been argued that persistence alone should be sufficient to restrict the use of a chemical[81,82].

Hazard data exist in a variety of different formats and databases. Hazard data are often classified according to the Globally Harmonized System of Classification and Labeling of Chemicals (GHS)[83], which has been adopted by individual countries to serve their regulatory needs[84]. Various lists of hazardous chemicals have been assembled by national and state agencies and non-governmental organizations for specific purposes [Table 2]. A major challenge is how best to interrogate and integrate these data. Recent studies provide examples of how multiple hazard criteria and databases can be used to identify and rank chemical hazards in plastics[1,2,29,30,85]. Key features include: 1) use of multiple sources to capture diverse types of hazards, including hazards to human and environmental health, as well as impediments to circularity[62,64]; 2) Development and utilization of explicit hazard-ranking models[29]; 3) Incorporation of information on potential exposure, including proxies such as production volume[2,29], while seeking more detailed data on exposure where possible. Additional guidance is available in proposed frameworks, such as that devised by the U.S. National Research Council[86].