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Using precision polymer chemistry for plastics traceability and governance

Hope Johnson, *†[a] Lewis C. Chambers,†[b] Joshua O. Holloway,†[b] Annastasia Bousgas,[a] Afshin Akhtar-Khavari, [a] James Blinco [b] and Christopher Barner-Kowollik *[b]

Resolving the anonymity of plastic materials is critical for safeguarding the well-being of our natural environments and human health. Herein, we explore how contemporary polymer chemistry – in the form of sequence-defined polymers and their enormous information depth potential, fused with progress in law and governance research – has the potential to significantly impact design standards, consumer behaviour, recycling systems and extended-producer responsibility schemes for plastic waste. We submit that chemistry and law need to work together in a true transdisciplinary effort to effectively combat the critical issue of plastic pollution.

Introduction

Reducing plastic pollution is a key challenge for societies worldwide, similar in scope and complexity to other large-scale environmental challenges such as climate change. Indeed, the United Nations (UN) has begun developing a global treaty to address plastic pollution, which is described as 'the most important' environmental global agreement since the Paris Climate Accord.[1] Consistent with the adoption of the circular economy paradigm in waste policy globally, governments, industry and international institutions are increasingly engaging with ways to improve the re-use and recycling rates of plastics and with developing whole-of-supply-chain responses. Meanwhile, the related issue of illegal transnational plastic waste trade has gained prominence following significant changes in transnational waste flows after China banned the import of certain plastic waste products in 2018.[2]

A key barrier to improving the management of plastics across supply chains is the lack of effective and sustained traceability along value chains.[3,4] The technical ability to trace plastics has been limited by various factors, including the ease at which plastics can be de-identified compared to other materials such as timber, the widespread manufacturing of plastics, and the wide variety of materials properties found in plastics. All of these factors allow the incorporation of plastics into a multitude of different, waste-generating applications. Fortunately, the technical ability to trace plastics has improved in recent years. The core aim of all (plastic) tracing technologies in chemistry is to embed information into the plastic itself in such a way that it can be easily and reliably read-out at the end of its use-cycle. Advances in tracing technologies will only reach their full potential when they are effectively incorporated into legal frameworks for plastics governance. Thus, now is the ideal time to highlight the technical capacity to trace plastics, along with the ways in which governments can use enhanced plastics traceability to combat plastic pollution.

Herein, for the first time, we draw on a fusion of legal and chemical science disciplines to summarise plastics traceability technologies and evaluate how new tracing technologies can be deployed by governments. To conclude, our contribution identifies future avenues to leverage synergies between chemical science and law research towards ending plastic pollution.

We will initially review the current state-of-the-art of chemistry available for coding, and importantly, reading information from plastic materials and subsequently conduct a similar audit of the current regulatory state. From there, we then explore future opportunities in a field that must necessarily fuse efforts of chemists, social scientists, and law makers to end the anonymity of plastic waste, which poses a critical risk to the well-being of humanity and our natural environment (refer to Scheme 1).

Emerging advances in plastics traceability in chemistry

The following section explores selected key methods developed for embedding information into plastics and for accessing this

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[a] *School of Law, Faculty of Business and Law, Centre for a Waste Free World, Queensland University of Technology (QUT), 2 George Street, Brisbane, QLD 4000, Australia. E-mail: h2.johnson@qut.edu.au*

[b] *School of Chemistry and Physics, Centre for Materials Science, Centre for a Waste Free World, Queensland University of Technology (QUT), 2 George Street, Brisbane, QLD 4000, Australia. E-mail: christopher.barnerkowollik@qut.edu.au*

† These authors have contributed equally.

Scheme 1 Fusing consumer plastic encoding using sequence-defined polymers with law research in a transdisciplinary approach to combat illicit plastic waste.

information further along the supply chain. These methods range from exploiting the inherently present information in polymers due to the nature of their chemical composition, to the addition of bespoke macromolecular entities that carry coded information. Specifically, we explore the potential of chemical labelling with sequence-defined polymers, which may overcome some of the technical and practical limitations of earlier methods. This perspective will highlight the overarching aim of many chemists to essentially introduce a unique identity, or a 'synthetic DNA', into commercial plastic commodities.

Spectroscopic identification

Exploiting the inherent molecular properties is one of the most obvious methods for plastics tracing. Beyond simply identifying and sorting polymers by density *via* flotation,[5] infrared (IR) and near-infrared (NIR) spectroscopy are perhaps the most powerful methods to characterise the chemical functional groups present in a material, which can in turn be employed as a fingerprint to identify the polymer or – at a minimum – narrow the material to a group of polymers.[6–10] This approach represents the most basic level of plastic tracing. It uses the intrinsic molecular properties of the plastic itself to facilitate identification. Unfortunately, the above approaches do not enable the tracing of a plastic material back to an original producer, unless a specific aspect of their production method or the specific molecular makeup of the polymer allows for a unique identification. In addition, material degradation over time can affect identification. To partly resolve this issue, it is also possible to incorporate small-molecule dyes or fluorophores into the material as a somewhat more specific label, which could theoretically be more precise than an NIR fingerprint alone.[11–17] However, the simple addition of dyes or other tracers, carries little information content that can be coded to a particular production batch.

Physical labelling

Imprinting the surface of a material constitutes an alternative simple approach to embedding information into plastics that offers more permanency than adhering a label.[18–20] This method has various benefits, including allowing for a broader range of information to be embedded than spectroscopic identification based on the molecular make-up of the polymer. The types of information that may be embedded include manufacturer, polymer type and batch number. Furthermore, if the surface reliefs are sufficiently small, they need not degrade the appearance of the material and, if numerous copies are included across the surface of the material, they stand a better chance of surviving to the end of the material's use cycle. While examples of this technology are less abundant than IR/NIR scanning, it is by no means unexplored. Digimarc, in collaboration with AIM-European Brands Association, have piloted digital watermarks that are the size of a postage code and can be decoded using a high-resolution camera.[21] Regardless, this technology has limitations with regard to the information density that can be encoded and the product type it is used for. Furthermore, such physical imprinting may not be applicable for large quantity products including plastic cups or bottles. Generally, information about the plastic composition can be provided, but it will not include information about, for instance, concomitantly present additives. Likewise, the ability to read the information will depend on the local context where the information is deciphered. Moreover, the embossed plastic will still degrade depending on the context and supply chain actors, especially in the context of illicit waste trading, which can potentially still remove the information.

Chemical labelling with sequence-defined polymers

In contrast to physical labelling strategies such as embossing, as discussed above, chemical labelling strategies can be used to embed the required information within the material itself. In considering possible molecular species able to encode information, an obvious class of candidates are biopolymers such as DNA, RNA and proteins, which encode information into the sequence of monomers linked together to form their chain. While these molecules may lack the stability to integrate into modern plastic manufacturing processes, synthetic sequence defined polymers apply the same principle within a more robust scaffold.

A plethora of sequence-defined polymers have been introduced over the last two decades and, herein, we only provide selected key examples to illustrate the current state-of-the-art. Inspiration is often drawn from nature and, therefore, it is not surprising that numerous biologically-inspired synthetic access routes exist. One such example includes enzyme-free DNA templated approaches to the synthesis of non-nucleic acid oligomers.[22,23] A further example is a DNA-templated approach, involving the incomplete hybridisation of DNA strands that carry individual monomers and the expulsion of the DNA as waste as the sequence is assembled.[24] Sequence-defined oligopeptides have also been used to synthesise macro-RAFT agents, which were subsequently employed for the synthesis of peptide–polymer conjugates through reversible deactivation radical polymerisations (RDRP).[25]

The solid-phase synthesis of sequence-defined polymers using phosphoramidite couplings has been extensively explored by Lutz and co-workers in the synthesis of non-natural polyphosphates, which have been used to write binary code in chemical form.[26,27] The similarity of these structures to that of DNA has enabled the use of biological read-out techniques – namely protein-based nanopore sequencing,[27] culminating in the synthesis of a sequence-defined polymer with a degree of polymerization (*i.e.* the number of building blocks within the polymer chain) exceeding 100, thus demonstrating the ability to synthesise precision macromolecules with an impressive (and as yet unsurpassed) number of repeating units, using a DNA synthesiser.[28] Alternatively, molecular machines have also been cleverly employed in the synthesis of sequence-defined polymers, whereby rotaxane molecules 'walk' along a 'polymer track' to 'pick up' and assemble amino-acid building blocks into a sequence-defined oligopeptide.[29,30] This strategy highlights the beauty of what can be achieved synthetically from a highly complex synthetic approach.

In addition to biologically-inspired examples of sequence-defined polymer synthesis, many synthetic routes exist.[31] The use of multicomponent reactions, most notably reported by Meier and co-workers, is an excellent example.[32] Both the Passerini three-component reaction[33–35] and the Ugi four-component reaction[36] have been used to synthesise sequence-defined structures of both high scale and purity.

As noted above, highly efficient and chemoselective reactions are essential for the synthesis of well-defined polymer architectures. As a result, click-chemistry has fast become the synthetic tool of choice for the sequence-defined chemist, which has just been rightfully honoured with a Nobel Prize to Bertozzi, Sharpless and Meldal.[31,37] Click-chemistry, first introduced in 2001,[38] has been used in countless sequence-defined synthesis routes (both biologically and synthetically inspired). For example, copper azide/alkyne cycloadditions (CuAAC) have been used to design iterative, orthogonal synthetic strategies,[39–41] as well as the post-modification of well-defined structures resulting in, amongst other examples, sequence-defined glycopolymers.[42–47] Diels–Alder reactions are also an important class of click reactions in this field, notably through the use of photochemistry as introduced by our team.[48–50] Thiol–X chemistries, which are arguably better described as click-like reactions,[51] have also been used as a highly efficient chemical platform for the synthesis of sequence-defined polymers.[52–55] Their numerous uses as a post modification handle in sequence-defined structures have been summarised in reviews.[37] However, one interesting and relevant adaptation of thiol–X reactions is thiolactone chemistry, where the cyclic thiolactone moiety serves as a protected thiol, thus circumventing some of the drawbacks of using thiols. Thiolactone can undergo a one-pot double modification reaction with an amine and acrylic moiety, resulting in a wide array of sequence-defined structures, which has been extensively researched by Du Prez and co-workers.[56–59] Many more examples of click-chemistry in sequence-defined polymer synthesis exist and have also been summarised in reviews.[32,37]

One interesting example of click-inspired sequence-defined polymers is that of data storage/encryption, a field closely related to the topic of this article, *i.e.* chemical labelling.[56,60–64] In both instances, the read-out of the coded information is key and will thus be discussed in more detail in the next section.

Decoding sequence-defined polymers

While one can readily perceive how sequence-defined polymers can be blended into plastic materials, reading their inherent information in a simple, cost-effective and fast fashion is a far more challenging task. Thus, the most critical and significant challenge when it comes to the storage or encoding of information in a new medium is the subsequent read-out, especially if the coded information is firmly embedded in a material such as a consumer plastic. The field is very much in its infancy and in the following section we explore the current state-of-the-art.

Much in the same way that data is stored on a computer, where storage must be in a readable format, data stored in chemical form needs to be recoverable at some point. By far the most prominent method for reading-out the information encoded into the structure of sequence-defined polymers is *via* high resolution mass spectrometry (MS). In particular, tandem MS/MS techniques have been widely employed,[49,56,60,61,63,65–69] though examples of single electrospray ionisation MS techniques as read-out methods also exist.[26,70] Tandem MS/MS enables the specific fragmentation of the sequence-defined structure, as determined by its molecular design. For example, the synthesis of oligo(alkoxyamine phosphodiester)s, which contain a readily cleavable alkoxyamine bond, resulted in predictable fragmentation patterns that can be read-out by a computer algorithm.[62] Tandem MS/MS based decoding was also effectively demonstrated by Du Prez and co-workers, who synthesised a range of sequence-defined oligomers using thiolactone chemistry. These were subsequently used to write short fragments of text to enable the writing and read-out of a sentence written in polymer form, analysed by MS/MS, which was then deciphered by computer algorithm.[56] The approach was even expanded to include the writing of a QR code, using sequence-defined oligomers. The underpinning synthesis was carried out *via* peptide-inspired solid-phase synthesis employing an automated synthesiser. In summary, tandem MS/MS enables one to decipher the precise monomer order based on the various fragmentation patterns.

High resolution mass spectrometry is undoubtedly a highly useful analytical technique, which has been employed in several ways for the successful read-out of sequence-defined structures. However, in terms of practical, real-world applicability, this technique has severe limitations. There is a high barrier to entry when using mass spectrometry, in terms of cost, availability, mobility, instrument size and required expertise, plus it is doubtful if MS based techniques can decode information embedded into plastic matrices. Diffusing this technology for practical applications in waste tracing, especially in low and middle-income countries may, therefore, prove highly challenging unless there is political will to significantly invest in such technologies to address plastic pollution. With the new UN treaty on plastics, there may be increased support for technology development and transfer arrangements that allow for the scaling up of mass spectrometry in the context of plastic recycling.

Despite these practical limitations, tandem MS/MS has been shown to be a powerful technique when it comes to effective use of sequence-defined polymers for data storage. Soete *et al.*, who developed rewritable molecular data systems, have brought the use of MS/MS read-out of precision macromolecules one step closer to that of modern data storage concepts.[67] Orthogonal cleavage of a position tag in a reversible manner, simultaneously coupled with a novel algorithm to assist read-out, neatly demonstrates the rewriting of sentences by a simple chemical modification. Alternatively, the usefulness of multicomponent reactions as a synthetic tool in the synthesis of sequence-defined polymers, as mentioned above, has also been employed in the chemical storage and encryption of information with again a read-out by tandem MS/MS.[60,63]

The unique structure of sequence-defined polymers makes them ideal candidates for chemical labelling (which can also be thought of as information stored on a polymer chain), even when imbedded in a polymer matrix, *i.e.*, a plastic material. To be able to chemically label polymer products to ascertain whether they are genuine has been achieved using isotopic patterning.[70] The inclusion of specific heteroatoms, affording predictable mass spectrometry patterns, can enable the identification of sequence-defined oligomers, giving more information than just the absolute mass value alone. This has been achieved using sequence-defined oligomers containing thermo-reversible Alder–ene bonds, which can be disassembled to encrypt the original information and yet the original sequence order can later be read-out by mass spectrometry.[70]

Molecular data encryption and stenography has also been demonstrated using a multitude of sequence-defined oligourethanes, containing both isotope labelling and halogen (isotopic) tags to assist deconvolution of complex mixtures of sequences.[71] This approach enabled a relatively high amount – 256 bits using hexadecimal code – of information to be stored in chemical form and was thus used as an encryption tool which can be deciphered by a third party. To the best of our knowledge, it represents the most amount of information to date stored in a single sample of abiotic sequence-defined polymers.

It should be noted that often applications using chemical labels involve these macromolecules being doped or blended within the polymer matrix, which leads to questions over their suitability or durability, including their potential for leaching-out. Concomitantly, regulators looking into embedding such technologies will have similar questions about leaching potential. Lutz and co-workers recently reported sequence-defined polymers, which are covalently bound to the material – in this case hydrogels – and retrievable by reactive desorption electrospray ionisation through a cleavable disulphide linker.[72] These binary encoded and material embedded labels were read-out by tandem mass spectrometry and since they are covalently bound, may significantly reduce the leakage risk over time.

For the true potential of sequence-defined polymers as a chemical labelling strategy to be realised, their incredible information density must be paired with the speed and ease of use of optical readout methods such as the infrared and near-infrared scanners, which have already been successfully integrated into plastic recycling facilities. We call on the polymer chemistry community to develop advanced read-out methodologies that fulfil the following criteria: (i) read out of the plastic embedded information with a hand held device useable in field-settings, possibly based on current hand-held mobile device technology, (ii) long term stability of the embedded code enabled by stable backbone connections based on C–C single bonds, (iii) high levels of variety in the code structure to enable the provision of unique identifiers, (iv) hard to impossible counterfeiting of the codes, (v) high sensitivity of the codes towards the read-out process so that they can be employed in low quantities (perhaps even in nanomolar concentrations) on a minimum cost basis.

Leveraging improved plastics traceability into law and policy

Provided that polymer chemistry can provide sequence-defined polymers as codes that fulfil the above criteria, their potential to advance law and policy regarding plastics is significant. Most of the research and related regulatory interventions for the governance of plastics focus on consumption and bans on single-use plastics leading to a situation where the production phase is 'not only under-regulated, but also under-researched'.[73] Traceability technologies expand the scope of legal strategies for plastics enabling a whole-of-supply-chain approach. Chemical tracing technologies, in particular, require regulation at the production phase to bring about the societal benefits of improved traceability.

We suggest that the regulation of plastics will critically benefit from chemical advances that allow us to resolve the anonymity of plastics traceability in five key areas. These are: design standards, consumer behaviour, recycling systems, extended-producer responsibility schemes, and combatting illegal waste streams. Further social scientific research is needed to adequately investigate the governance potential of traceability technology.

Design standards

Design standards, or eco-design principles, are design approaches aimed at reducing the environmental impacts of products and services along that product's entire lifecycle. Eco-design principles define how a product is made, used, maintained and disposed of at the end of its life, with the goal of maintaining a products quality and/or minimising negative environmental impacts.[74] These standards may be mandatory (*i.e.* manufactures have to adopt) or voluntary (*i.e.* the government or other stakeholders creates incentives for compliance with the standards).

Design standards for plastics are increasingly aiming to increase the durability and ability to repair plastics, increase the ease at which plastic products can be disassembled, mandate a certain amount of recycled plastic content and limit the types of additives and chemicals used in plastics production to make recycling more straight-forward and cost-effective. In the European Union (EU), for instance, the *Single Use Plastics Directive* sets a mandatory recycled plastic content of 30% by 2030. Similarly, the EU's *Eco-design Directive* and the *EU Ecolabel* also provide examples of how product requirements are being used to influence design characteristic of plastic products, such as the physical marking of plastic components to assist in disassembly and dismantling, the listing of polymer composition, increasing the use of recyclable polymers and increasing availability of information on material composition.[75] Accordingly, the EU, as well as some other jurisdictions, use to an extent the physical labelling approach examined previously, but as discussed there are practical limitations to this approach to sharing information.

Chemical labelling – including with sequence-defined polymers – would require changes to design standards to encourage manufacturers to use these polymers and to require certain information be embedded into the polymers. Depending on the information embedded, chemical labelling using sequence-defined polymers could be deployed to monitor the percentage of recycled plastics incorporated into new products and to identify the polymer material composition of products coming into the market of any country. This information is not only useful for creating a feedback loop, whereby regulators can assess the effectiveness of design standards, but could also assist local waste managers plan for targeted investment in end-of-life processing for the type of plastics prevalent within the local market. Chemical labelling could also be used by jurisdictions like the EU, to uphold and verify claims against policy requirements to reduce and eradicate certain hazardous substances. In addition, chemical labelling may allow for improved data collection related to tracking of the overall reduction in certain types of plastics and certain types of additives to monitor how well design standards are working.

Consumer behaviour

Although it forms only part of the context that regulators need to address, interventions to influence consumer behaviour are highly important in the context of plastics. Reducing consumer consumption of plastics where feasible and encouraging better consumer purchase choice for products has been a focus of regulators worldwide.[76] This focus is linked to the idea that plastic avoidance leads to less waste and that better consumer use and disposal of plastics would improve the quality of recycled plastic material. Enabling consumers to choose particular kinds of plastics also has the potential to act as an incentive for industries to incorporate more sustainable plastic design elements, such as recycled content, into their product. Similarly, involving consumers in the sorting and disposal of plastics can improve the recyclability and increase re-use of plastics, and reduces contamination of recycled plastic streams. To date, the focus of governments when it comes to influencing consumer behaviour has been on public campaigns regarding recycling and avoidance of litter, improvement of recycling labels, as well as bans on particular kinds of plastics.[77]

Yet, research continues to identify "perennial problems with consumers' ability to sort waste correctly",[76] partly because recycling plastic is particularly complicated. Consumers face not only numerous types of polymers within their plastic products (including blends), but are also expected to decode and apply varying waste sorting systems and instructions for disposal related to any one product containing plastics. These factors can cause confusion, concern and act as a general psychological barrier to engage in sorting and involvement in proper disposal practices. As such, consumer studies indicate that the most important barriers to consumer's properly sorting waste are lack of knowledge and understanding, as well as lack of opportunities, inconvenience, and task difficulty.[76]

Recycling labels are intended to guide consumers to address these barriers, but they are limited in the amount of information they can convey to consumers. For example, the Australasian Recycling Label used in Australia and New Zealand only has the ability to indicate whether the product should be placed in the rubbish bin or is likely to be recyclable or is recyclable but only in particular contexts (*e.g.*, if it is flattened or returned to a drop-off point). There is no ability to include further information on these labels, such as whether the product requires washing prior to disposal, whether only parts of the product are recyclable or if the local recycling system actually recycles that type of plastic. Accordingly, 64% of Australian consumers want more information about what can be recycled.[78]

Improved plastics traceability technologies that are low-cost and easily accessible will significantly reduce these barriers. Allowing consumers to scan plastic products using, for *e.g.*, their smart phones to determine the type of plastic and proper disposal method will be a key to improve not only disposal practices, but critically the level of recycled plastics collected for processing. Ultimately, such interventions will be limited by other factors, such as the level of environmental concern a consumer has and the quality of local waste infrastructure. However, when combined with improvements in infrastructure and with a concerted effort to build a culture around re-use and recycling by stakeholders, such interventions can play a particular important role.

Recycling systems

Global recycling of plastics maintains low rates of utilisation, sitting at just 9%.[79] The reasons why recycling rates remain low are complex, but broadly relate to the high cost of collecting, sorting and recycling materials.[80] The fluctuating costs associated with obtaining and utilising recycled polymers compared to virgin material remains a continuing issue, which policies such as the *EU Packaging and Packaging Waste Directive* seek to address.[81] Moreover, technical inefficiencies leading to an overall lack of information regarding the availability of recycled plastics, the quality of the polymers produced and recycled plastics suitability for use for further applications acts as a disincentive for using recycled material.[82,83] The technological advances detailed above may improve access to plastic composition information that could contribute to resolving some of these issues. In fact, spectroscopic identification is already used in some recycling facilities.

Chemical labelling with sequence-defined polymers allows for the accurate identification of the type of polymer and, potentially, the type of additives used in the manufacturing process. This is especially important as additives increase not only the difficultly of sorting plastics but also the risk of contaminating the material stream thus reducing the quality of the secondary material. Similarly, improved access and accuracy of information at the time of sorting would improve the purity and quality of the recycled polymers produced, and better allow for the identification of the suitability of various recycled plastics to be used for further applications. For chemical labelling to function in this context, information would need to be embedded into the resin pellets that identify the additives that will ultimately be used in conjunction with the nurdles. This would require strong supply chain coordination whereby actors isolate nurdles based on where they are going to next in the supply chain and embed certain quantities of nurdles with information about the likely additives. Ultimately, governments and other stakeholders will need to scale-up investment in waste infrastructure to use chemical labelling with sequence-defined polymers as a way to improve plastics recycling.

Extended producer responsibility schemes

Extended Producer Responsibility (EPR) schemes are the leading way countries currently respond to plastic waste. EPR schemes allocate responsibility to those who place products on the market (*i.e.* producers), either financially and/or logistically, for their products when they become waste at the end of their useful life. These schemes can be mandatory but also voluntary in nature.[84] Responsibilities may include offering free collection sites for consumers to dispose of the product after use and funding the collection and processing of waste. Depending on the scheme, manufacturers may undertake these responsibilities themselves or, far more commonly, they will pay into a collective scheme that takes care of these responsibilities on their behalf. Generally, they pay a certain amount, calculated using various means such as the amount of waste their products generate, to a Producer Responsibility Organisations (PRO).

Depending on the type of information imbedded chemically in plastic traceability technology, EPR could significantly benefit from improved traceability. Firstly, information included that relates to the type of plastics would greatly improve the overall data about the amount and type of plastic going out onto the market, and would also improve data related to the types and amount of plastics being collected through EPR schemes. Secondly, improved ability to trace plastics would increase the accuracy of determinations about how much plastic waste was being generated by the use of a company's products, which in turn could be used to more effectively determine the fees a manufacturer should pay into the EPR scheme. Thirdly, improved traceability that included increased information about the additives included in plastic products, could be used to track whether and how producers are making improvements to their products under these schemes. This information could also improve design outcomes, with higher fees set for plastics that include additives in plastic packaging that are not hazardous but may disrupt end of use processing in other ways, such as contaminating the recycled material.

Combatting illegal plastic waste streams

Illegal plastic waste trade refers to waste created in one country and exported to another in a manner that breaches domestic or international laws. The International Criminal Police Organization (INTERPOL) has reported a rapid increase in illegal plastic waste trade since 2018, with illegal waste shipments being primarily sent to South and South-East Asia.[16] Generally, it occurs through a re-routing of illegal plastic waste shipments through various countries to make the origins of the waste difficult to uncover. The use of fraudulent documents and/or a false declaration of what is contained in a shipment is also common.[85,86]

Amendments to the annexes of the 1989 *Basel Convention on the Control of Transboundary Movements of Hazardous Waste and Their Disposal* in 2021, mean that member countries now have to control the trade of non-hazardous, mixed or hard-to-recycle plastic waste, and only export such plastics to jurisdictions that have either consented or allow that particular kind of plastic waste imports.[87] Member countries are also obligated to create domestic procedures to ensure that countries accepting their plastic waste have the capacity to dispose of that waste in an 'environmentally sound and efficient manner'.[87] Meanwhile, the EU, Canada and Australia have imposed bans on the export of particular kinds of plastic waste, for example *Recycling and Waste Reduction Act 2020* (Cth) bans the export of unsorted plastic waste from Australia[88] with the *Delegated Regulation (EU) 2020/2174 Plastic waste shipments and Waste Shipment Regulations* similarly banning such export in the EU. The UK is considering a similar ban on the export of plastic waste to low-income countries.[89]

These bans, while useful, have limitations in their ability to prevent illegal waste streams, as multiple interventions are required at domestic and transnational levels. Improved tracking of waste, through various means, is widely recognised as a key way to address illegal plastic waste trade by improving border checks and reducing the potential for false declarations.[90] To date, the focus has been on how digital methods of collecting and verifying waste information can be improved to reduce illegal waste exports, with the UK leading the way with its development of a digital waste tracking system for domestic waste flows.[91] However, there is capacity for digital methods to be used alongside chemistry-based methods for plastics traceability. For instance, border checks on samples of plastics could employ chemical labelling using sequence-defined polymers to check the origins and type of plastic being traded, which is then reported back into a digital waste tracking system. Furthermore, low-cost methods to determine the type of plastic may improve the safety for informal waste pickers in low-income countries subjected to large amounts of unregulated plastic waste.[2]

Conclusions

We have highlighted the most recent advances in contemporary polymer chemistry, particular in the field of sequence-defined polymers, to mount an argument that these structures are – at least in principle – ideally placed to resolve the anonymity of plastic materials and advance the governance of plastcs. By resolving the anonymity of plastic materials and making them traceable, novel governance arrangements can be developed using insights from chemistry and social sciences, particularly law. The development of the UN treaty on plastics will put more pressure on governments and industries to invest in technologies like sequence-defined polymers combined with new legal approaches. Questions such as what information is required to be encoded, for how long does the information need to be stably encoded, what is the maximum that coding can cost, which polymer types should be coded, how can coding be mandated and what read-out mechanisms are appropriate are key questions yet to be answered. These questions can only be answered by (polymer) chemists working with legal and other social scientific disciplines focused on how best to adopt and diffuse a technology and drive social change. Perhaps most critically, true transdisciplinary research efforts between the social sciences and chemists – or translated to a societal level between plastic producers and law makers – have to commence at an early point in the innovation cycle for plastics control within complex supply chains. The current article is a call to action for the social and natural sciences – using the example of plastics tracing – to commence serious collaborative efforts to tackle the most critical, complex challenges that beset our planet. Siloed structures, including at universities, where social and the natural sciences are separated are not conducive to overcoming these challenges.

Conflicts of interest

The authors have submitted a priority patent application in the realm of plastic tracing technology, owned by their employer QUT.

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