The message ~~in~~ on the bottle:

Rethinking plastic labelling to better encourage sustainable use

Stephen D. Burrows*[1,2], Francisca Ribeiro[1,2], Stacey O'Brien[2], Elvis Okoffo[2], Tania Toapanta[2], Nathan Charlton[2,3], Sarit Kaserzon[2], Chun-Yin Lin[2], Cheng Tang[2], Cassandra Rauert[2,3], Xianyu Wang[2,3], Katja Shimko[2], Jake O'Brien[2], Piers A. Townsend[4], Matthew N. Grayson[4], Tamara Galloway[1], Kevin V. Thomas[2,3]

[1]College of Life and Environmental Sciences, University of Exeter, UK
[2]Queensland Alliance for Environmental Health Sciences (QAEHS), The University of Queensland, Australia
[3]Minderoo Centre – Plastics and Human Health, University of Queensland, Queensland, Australia
[4]Centre for Sustainable Chemical Technologies, Department of Chemistry, University of Bath, U.K
**Corresponding author: sb982@exeter.ac.uk*

Abstract

Plastic pollution continues to worsen globally in volume and complexity. The complexity in plastic production, use and disposal is significant, highlighting the importance of clear communication to consumers. Yet despite this, poor plastic labelling is clear, evident from poor waste management metrics even in the most equipped countries. Plastic labelling must change to contribute to a holistic intervention on global plastic mismanagement. Discussion on this topic leads to three key recommendations: 1. An accurate and clear "sustainability scale" to empower consumers to make decisions informed by environmental and human health implications; 2. Directions for appropriate disposal action in the region of purchase; 3. A comprehensive list of plastic composition, including additives.

1. Introduction

1.1 An ever-growing problem

Plastic pollution has now permeated through the world's ecosystems, from Arctic ice, the bottom of the Mariana trench, to the slopes of Mount Everest (Chiba, et al. 2018, Halsband and Herzke, 2019; Napper, et al. 2020, Peng, et al. 2020). The primary cause is high production and widespread mismanagement of plastics as a resource, with about 368 million tonnes produced annually (2019 estimate from PlasticsEurope, 2020). Around 80% of the plastics produced still exist, having been dumped into landfills or released into the environment (Geyer, et al. 2017).

While there is a significant drive to change our relationship with plastics (evident from recent relevant legislative intervention propelled by consumer advocacy) (da Costa, *et al.* 2020), the issue continues to worsen (Lau, *et al.* 2020). Highlighted in models, such as the Plastics-2-Ocean model by Lau, *et al.* (2020), even the most ambitious interventions will not completely stem the flow of plastic into the environment. However, they do make clear that the issue will become significantly worse if substantial action is not taken soon (Lau, *et al.* 2020).

Without a real-world applicable circular economy for plastic (given known issues from legacy additives, through to product degradation during recycling (Borrelle, *et al.* 2020; Matthews, *et al.* 2021; Wagner and Schlummer, 2020), there is no single, all-encompassing solution to rectify and mitigate our mismanaged relationship with plastics as a resource. The plastic pollution issue is multifaceted, and a key component to the problem is consumer miscommunication.

1.2 Issues with labelling

"Miscommunication" here refers to the labelling of plastic items. Based on present rates of recycling, estimated between 30% and <10% in China, Europe and the USA, labelling is ineffective at encouraging sustainable use (Geyer, et al. 2017; Lazarevic, et al. 2010). While plastic waste labels can differ by geographical region, they share clear limitations that contribute to their ineffectiveness (Figure 1).

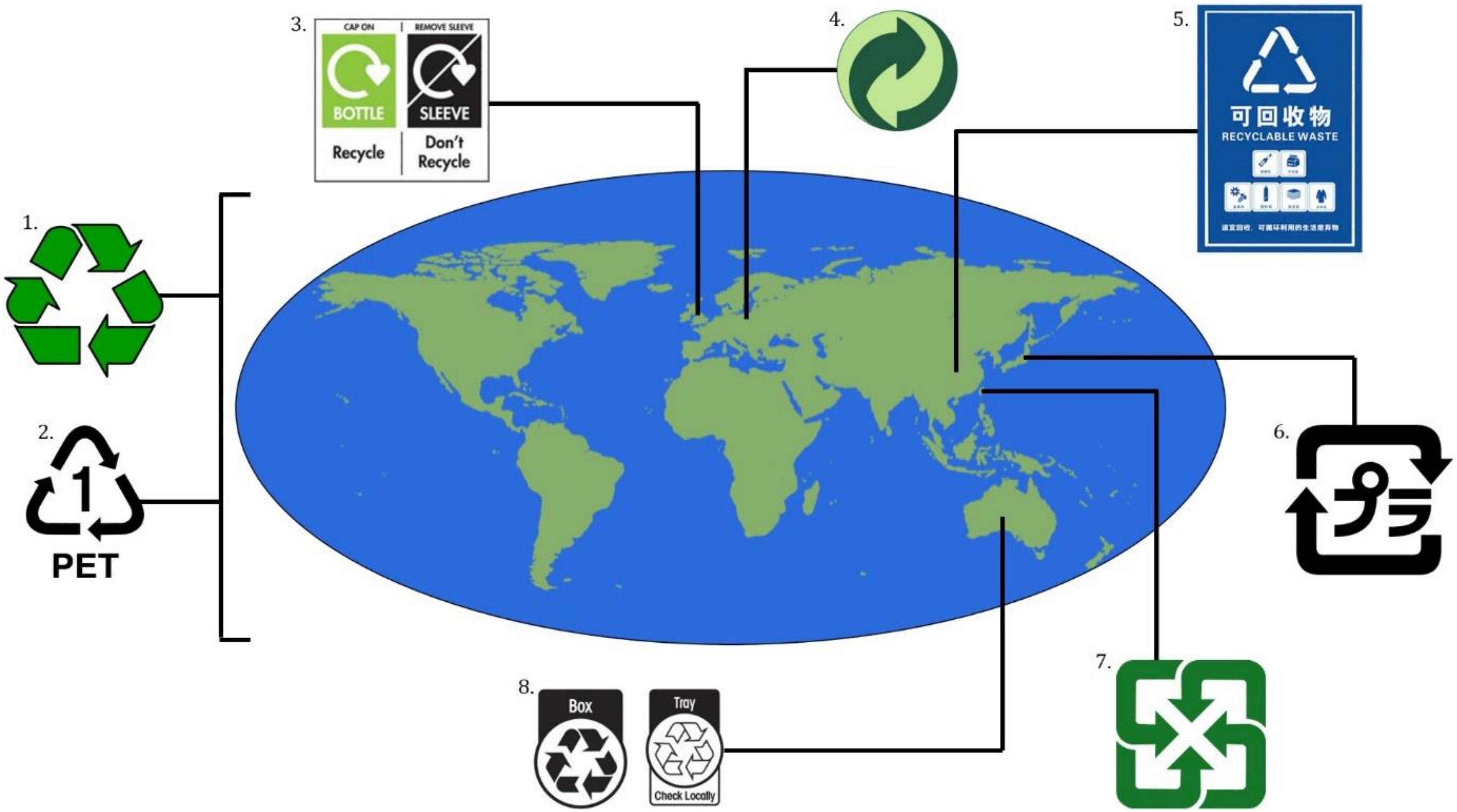

Figure 1: International, UK-, European-, Chinese-, Japanese-, Taiwanese- and Australasian-specific recycling labels (Office of the State Council, 2017; Planet Ark, 2020; Recycling Fund Management Board, 2021; Sakura City, 2021; Wrap, 2021). 1. Mobius Loop Recycling Symbol, 2. International plastic resin code. 3. "RecycleNow" recycling labels (UK). 4. "The Green Dot" (EU). 5. "Recyclable" Chinese Recycling label (China). 6. Recyclable Plastic Symbol (Japan), 7. Recyclable Plastic Symbol (Taiwan), 8. "Recyclable" and "Conditionally recyclable" Australian Recycling Labels.

Credible and relevant information is key to enabling the public to make more sustainable decisions. Despite this, plastic labelling oversimplifies and often unintentionally misinforms the public regarding the sustainable handling of plastic waste. Plastic labels can falsely indicate a product is recyclable, for example through the use of the International Plastic Resin Symbols, The Mobius Loop from the UK and The Green Dot from the EU (Figure 1.1,2,3) (WRAP, 2021). Labelling largely does not indicate regional recyclability, and when it does (Figure 1), it places the burden on the consumer to investigate for further information (WRAP, 2021; Planet Ark, 2020).

1.3 Increasing complexity - new materials and additives

These shortcomings in contemporary plastic labelling, alongside projected continued increases in plastic production are not the only drivers behind the urgency to improve labelling (Borrelle, et al. 2020). Commercial use and labelling of new materials such as copolymers, bioplastics, biodegradable, oxo-degradable and compostable plastics add further confusion for the consumer (Napper and Thomson, 2019). Furthermore, weak regulation of plastic additive chemicals complicates the matter further. There is significant need for more rigorous risk assessment before commercial application, to control human and environmental exposure to potentially toxic chemicals (Galloway et al., 2018, Ferguson, *et al.* 2019).

Based on the above points, plastic labelling does not adequately reflect the complexity of the subject, nor does it facilitate sustainable use. To do this we must urgently adapt and standardise current labelling approaches to become more effective (American Chemistry Council, 2021; Borrelle, et al. 2021). Here, we recommend a more effective plastic labelling system, which considers three major components; petroleum-based plastics, new and “sustainable” plastics, and chemical additive content.

2. Petroleum-based plastics

2.1 Defining petroleum-based plastics

According to the International Union of Pure and Applied Chemistry (IUPAC), a polymer is a "molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass" (Jones, *et al.* 2008). Petroleum-based plastics are included in this category as synthetic polymers obtained from natural gas or oil, that usually include stabilizers and/or plasticisers to enhance the efficiency and durability of these materials (Andrady, *et al.* 2009; Thomson, *et al.* 2009). The main petroleum-based plastics include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) (Hartmann, *et al.* 2019).

These plastics constitute the majority global domestic plastic waste (approximately 87%) and are divided into six main categories (1 – 6) and a broad "other" (7) (Table 1), through an International Resin Identification Coding System originally attributed by the Society of the Plastics Industry (SPI), also recently administered by the American Society for Testing and Materials International (ASTM) (Rahimi, *et al.* 2017). These categories were attributed by the SPI to facilitate sorting plastic products in recycling centres (Scalenghe, 2018).

Table 1. International Resin Identification Coding System for plastics, paired with 2018 estimated percentages recycled of the plastic produced in the USA that year (Environmental Protection Agency, 2018; Merrington, 2017; Rahimi and García, 2017).

SPI number	Plastic name	Symbol	Examples of applications	Percent Recycled in USA 2018
1	**PET**	PETE	Disposable bottles for drinks, fibres (clothing, carpet), film, cosmetic packaging, food containers	18.5%
2	**HDPE**	HDPE	More durable non-food containers, buckets, crates, recycling bins, floor tiles	8.9%
3	**PVC**	PVC	Piping, cables, garden furniture, fencing, decking, panelling, floor tiles and mats, traffic cones, electrical equipment	<1%
4	**LDPE**	LDPE	Plastic bags, trays and computer components, wrapping films, trays	4.3%
5	**PP**	PP	Car parts , signal lights, oil funnels, brushed, yogurt containers, bicycle racks, bottle caps, reusable food containers	< 1%
6	**PS**	PS	Thermal insulation, foam packing, take-out food containers, disposable cutlery	< 1%
7	**Other**	OTHER	Polycarbonate (refillable plastic bottles, consumer electronics) nylon (clothing, carpets), biodegradable resins, mixed plastics and blends (electronics housing, plastic lumber)	26.7%

2.2 Definition of contemporary recycling

The concept of “recycling” plastic is defined here as the process of recovering plastic waste and transforming the material into useful products (Merrington, 2017). Plastics usually undergo a similar recycling process (mainly for primary and secondary recycling). Generally, they are collected, transported to the recycling facilities, sorted by resin type, washed, and dried to remove dirt, and ground into fine powder/particulate matter (Rahimi and García, 2017). Depending on the desired end-product, further preparation through the addition of additives may also be undertaken (Rahimi and García, 2017). Four main types of plastic recycling are commonly described: *primary* (“closed-loop” recycling, where intact recovered material is used for the same purpose as the original plastic), *secondary* (mechanical recycling, where material is mechanically ground to produce a broad range of products that have less demanding performance requirements than the original material), *tertiary* (chemical recycling, recovers a mixture of monomers by exposing recyclate to elevated temperatures in the presence of a catalyst and absence of oxygen) and *quaternary* (incineration, with or without energy recovery) (Singh, *et al.* 2017) (Figure 2). While the International Resin Identification Code symbols (showing the triangle of arrows), appear to imply sustainable use of petroleum-based plastics is possible through recycling, this is not universally the case (Table 1).

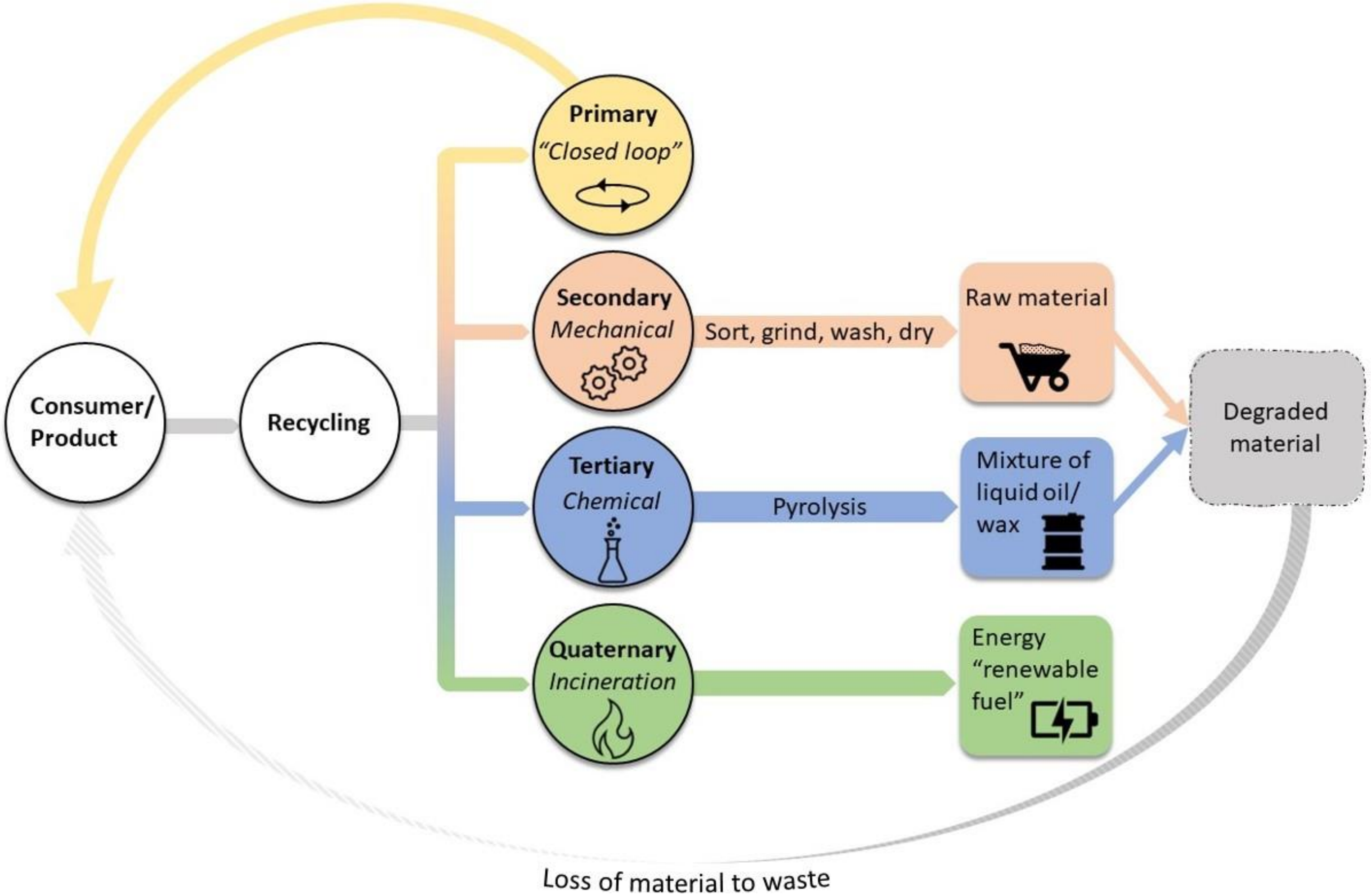

Figure 2 - A summary flowchart of the recycling processing including: primary ("closed loop") secondary (mechanical), tertiary (chemical), and quaternary (incineration) recycling.

2.3 Challenges to effective contemporary recycling: diversity in plastic material

In Europe, China, and the United States, 30%, 25% and less than 10% of plastic is recycled, respectively (Geyer, *et al.* 2017; Lazarevic, *et al.* 2010). Plastics with the highest recovery rates are PET, high-density polyethylene (HDPE), low-density polyethylene (LDPE), and PS, although global recovery rates are typically reported as below 20% (Rahimi and García, 2017). For other resins, as reported in Table 1, recoveries are generally between 0-1% (Rahimi and García, 2017). The primary difficulty associated with the recycling of these polymers is the sheer number of possible additives, coatings or treatments (some of which are known toxicants) that are incorporated into most products derived from plastics. This complicates matters for recycling companies when it comes to the recovery of plastics for reuse (Merrington, *et al.* 2017).

The specific challenges and effective recycling rates associated with each plastic type can be addressed individually: PET (code 1) is a durable and malleable plastic broadly used in consumer products, though only a small portion is recycled for its original application since its malleability is compromised by more than 95% by the third recycling cycle. Consequently, 50 to 77% of PET is converted to fibres to produce mixed material (La Mantia, 2002).

The recycling processes for HDPE (code 2), LDPE (code 4) and PP (code 5) are remarkably similar, belonging to the group of polymers called polyolefins (Rahimi and García, 2017). These can be mechanically recycled, but over time become less stable (Rahimi and García, 2017). While methods of chemical recycling for these polymers poses a potential way to circumvent this issue, chemical recycling is complicated and remains prohibitively expensive (Rahimi and García, 2017).

PVC (code 3) is one of the most durable polymers owing to the blended additives incorporated in its composition. A significant drawback of the additives used in PVC-based materials is that they can easily contaminate entire batches of polymers in recycling plants (Rahimi and García, 2017). This additive content in PVC-containing materials is also problematic as it can leach for example, phthalate plasticizers and chlorine-containing organics during degradation (Rahimi and García, 2017).

The low recovery rates associated with PS (code 6) are mainly due to waste separation. In regard to PS production, 10% is EPS (expanded polystyrene), 50% is in the pure form and the remainder is blended with other materials (Goodier, 1961; Wünsch, 2000). Diversity of end-products, paired with variances in polymer density, complicates the sorting mechanism at the recycling centres.

Category 7 includes all other plastic polymers: polyurethane, polyurea, polycarbonate, nylon, poly(methyl methacrylate) (PMMA), high-performance thermoplastics, and thermosets such as epoxies and biopolymers (Rahimi and García, 2017). The use of thermal and photochemical approaches to polymers such as PMMA, the thermoplastic PES (polyethersulfone) and some nylon types, can allow for effective depolymerisation of these plastics to their monomer units (Rahimi and García, 2017). However, each polymer group has its own recycling challenges, in addition to required consideration of possible additive content and composite formations (Rahimi and García, 2017).

Manual separation of resins can be time consuming and inefficient. Although automated techniques have been optimised to distinguish between diverse polymer types by identifying specific optical, density and spectroscopic properties of the plastic (Merrington, 2017), their performance is not always effective (Rahimi and García, 2017). In addition, the sheer variety of plastic additives makes them a significantly complex issue to unravel in terms of recycling efficacy.

2.4 Challenges to effective contemporary recycling: regional dependence

Although the lack of good recycling practices by consumers is frequently identified as the main factor for low recycling rates, technological limitations are the key limiting factor on the efficiency and broad-scale adoption of plastics recycling. Consequently, the recyclability of plastics is geographically dependent, and should be considered in a regional, rather than a national or global perspective (Kollikkathara, *et al.* 2009; Kumar, *et al.* 2017).

A clear example of this variation is shown when comparing two different regions of the globe, here Germany and the United States of America (USA). European Union (EU) member countries follow a series of strict guideline and targets established by the EU; previously the "Zero plastics to landfills by 2020". Currently, the target for 2030 is to recycle 65% of municipal solid waste (Žmak, *et al.* 2017). Among EU countries, Germany has the highest rate of plastic recycling (62%) and one of the lowest landfill rates (Žmak, *et al.* 2017). This is the result of schemes implemented by the German government that include: the "Green Dot" service - a dual disposable system for used sales packages, the public waste disposal service, and the plastic bottle deposit system (Hopewell, *et al.* 2009; Žmak, *et al.* 2017). This advanced plastic recycling capability is also possible due to available infrastructure. Germany has 68 operating waste incinerating plants with a total capacity of 20 million tons of plastic (Žmak, *et al.* 2017).

In contrast to Germany, the USA reportedly recycles less than 8% of its plastic waste (Heller, *et al.* 2020). This is primarily due to the "National Sword" program implemented by China in 2018, which banned the import of almost all plastic waste (Clarke, 2019), of which the USA was a major contributor. As such, the USA does not currently have sufficient infrastructure in place to process its plastic waste. Furthermore, the USA now exports most of its plastic waste to Malaysia, Vietnam, Indonesia, and Thailand instead. The effectiveness of this strategy for recycling is poor, as a large percentage of the plastic waste exported remains unprocessed, as these countries also lack the facilities for sufficient sorting and reprocessing (Heller, *et al.* 2020). Law, *et al.* (2020) estimated that in 2016 between 0.15 to 0.99 million tonnes of plastic waste collected for recycling was mismanaged in other countries.

This dichotomy between two wealthy countries, with respect to plastics recycling, highlights the regional variability in this issue. Unless recycling strategies are economically viable and sufficient infrastructure is available, they are unlikely to be successful (Joshi, *et al.* 2019).

2.5 Shifting focus from recyclability to sustainability

Based on the nuance regarding what dictates "recyclability", from the interference of different additive components to the regional availability of infrastructure, a better solution would be to present recyclability on a scale rather than a categorical characteristic on labels. Going further, solely focusing on recyclability is not going to solve the plastics issue. Consideration of other associated environmental and human health risks is needed. Factors such as: product lifespan, use of additives, the environmental impact of sourcing material etc, all have an environmental cost that should be communicated to the consumer. Despite the significance of these values to the true "sustainability" of plastic products, the main message to the consumer is primarily a categorical recyclability label. There is a gap here, in the development of a more sustainable plastics industry, for a more accurate labelling system including a sustainability index.

A sustainability index for plastic materials would require careful consideration of which factors in environmental outcomes (including leachate, end-of-life processing, material use and degradation behaviour) and life cycle assessments (LCA) are significant to the "sustainability" of plastic (Huisman, *et al.* 2003). An example of what such an assessment could look like would be the LCA perspective by Kouloumpis, *et al.* (2020), in which the carbon footprint of PET bottles versus glass bottles was assessed in Cornwall (UK), using high-resolution data on a local scale regarding available waste infrastructure to transportation. Making this information easily accessible and understandable to consumers would be an example of how to better facilitate sustainable plastic use.

The onus to understand complex, technical, and sometimes misleading disposal processes and product attributes is placing an unreasonable expectation and burden on consumers (Boz, *et al.* 2020). Current labelling systems for plastic products are not practical and do not facilitate sustainable use. Rather than more categorical labels indicating end use, there needs to be a more holistic system which reflects the complex issue of real-world plastic manufacturing, use and disposal.

3. Bioplastics and "sustainable alternatives"

3.1 Defining bioplastics and new "alternative" materials

Switching to bioplastics and other "sustainable alternatives" has been purported to play a key role in tackling plastic pollution (Iles and Martin, 2013; Lamberti, *et al.* 2020). The term "bioplastics" is used for two separate groups of plastic material: bio-based plastics, which are derived from plant or animal matter, and biodegradable plastics which include 'Oxo-biodegradable' plastics (made with various additives which catalyse degradation) and 'compostable' plastics (which should be 90% chemically broken down within 180 days, given specific compositing conditions, according to the American Society for Testing and Materials (ASTM International, 2019)) (Fojt et al. 2020) (Figure 3). Replacing petroleum-based polymers with bioplastics is expected to reduce the demand for fossil fuels, potentially reducing carbon emissions. The shift towards bio-plastics has slowly increased in the past decade, where today they represent about one percent of the more than 368 million tonnes of plastic produced annually (Plastics Europe 2020; Fojt et al. 2020). Bio-plastics can include few or several components and are typically divided into (i) bio-based plastics such as polyesters, PE, PET, polyamides (PA) and polyurethane (PUR), (ii) bio-based and degradable plastics such as polylactic acid (PLA), polyhydroxyalkanaoates (PHA), polybutylene succinate (PBS), and (iii) fossil-based but biodegradable plastics- such as polycaprolactone (PCL) and polybutylene adipate terephthalate (PBAT). Bio-based degradable alternatives are forecast to increase. In particular, products such as PLA and PHAs are increasing in popularity showing high growth rates due to their complete biodegradable behaviour under certain aerobic and anaerobic environments and potential as commercially viable compostable plastic material (Meereboer et al. 2020; Rujnic-Sokele & Pilipovic 2017). Among the challenges associated with these products are higher production costs and the need to incorporate organic fillers and fibres primarily composed of cellulosic material to strengthen the properties of polymers. These could impact the degree, and extent of, biodegradability of the product and the biodegradation efficiency between industrial and household composting environments and in marine systems (Meereboer et al. 2020; Song et al. 2009; Haider et al. 2019). End-products may not sufficiently degrade once in the environment or potentially deliver different leachate due to addition of chemical additives meant to increase the durability of products (Lambert & Wagner 2017).

The debate remains whether bioplastics production truly relieves pressure on the environment. The topic is complicated by production details specific to each product in question, from the environmental cost of sourcing their raw materials, to required land use at scale, paired with the need for commercial viability and competitiveness regarding financial cost (Music, *et al.* 2022). It is debatable if they are better for the environment over conventional plastics and if they add to, or solve existing problems observed with their non-degradable counterparts, related to the miscommunication on, and the disposal of these products.

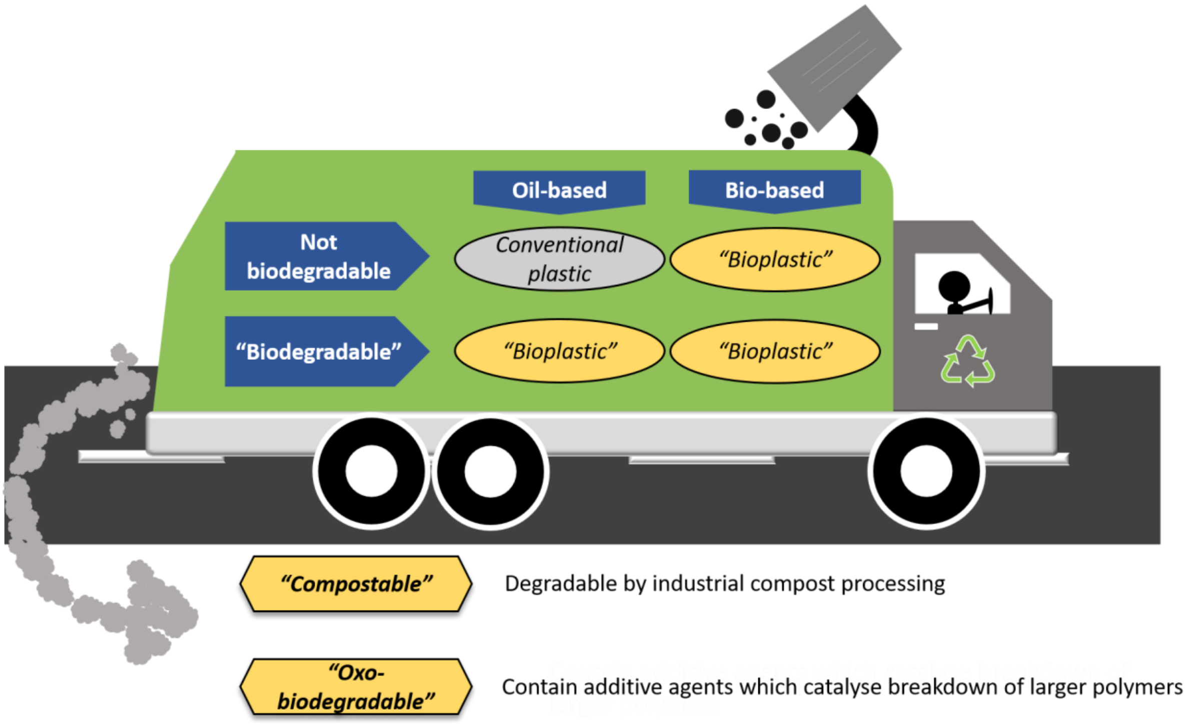

Figure 3 – Defining "bioplastic" and "biodegradable" in a real-world context, as well as "compostable" and "oxo-biodegradable" within "biodegradable"

3.2 Miscommunication of correct disposal methods

According to Dilkes-Hoffman et al. (2019ab), a plastic material which breaks down through the natural action of microbes including algae, fungi and bacteria resulting in water, biomass, methane, and CO_2 without producing any residual by-product is truly biodegradable. Those that can breakdown due to catalysing additives ''Oxo-biodegradable plastics'' are not truly biodegradable, as they can leave residual micro-fragments accelerating microplastics pollution (European Bioplastics, 2015). Currently there is confusion among bioplastics end-of-life labelling, with terms like "biodegradable", "compostable" and "bio-based" plastics not clearly defined, making it harder for consumers to make environmentally responsible choices (Napper and Thomson, 2019).

Generally, when thinking about bioplastics, consumers associate biodegradability as a key factor together with environmental friendliness, sustainability, and non-toxicity (Haider et al., 2019). However, the reality is, there are materials labelled biodegradable, compostable or bio-based today which are not suitable for disposal in the open environment (Haider et al., 2019; Dilkes-Hoffman et al., 2019a, b). A typical example is bio-based PET which polymer chains can be synthesized from oil-based or renewable sources such as sugarcane, both resulting in the same or chemically identical material. Such non-biodegradable bioplastic will behave exactly as a conventional plastic in the environment and could persist for an unknown amount of time (Napper and Thomson, 2019).

Not all biodegradable plastics are biodegradable under the same conditions (Dilkes-Hoffman et al., 2019ab). Polylactic acid (PLA), the common type of bioplastic derived from plant like materials and marketed ‘’biodegradable’’ is a typical example. Although biodegradable and compostable, PLA will not biodegrade in all environments, as it requires specialised industrial composting processing facilities and specific conditions/circumstances (e.g. higher temperature), contingent on proper management (Gorrasi & Pantani, 2017). This makes PLA technically an industrially compostable plastic rather than biodegradable (Gorrasi & Pantani, 2017). This important information is either not mentioned or ignored on product labelling.

Furthermore, although the public may assume that all bioplastics are recyclable, there are complications with this assumption. The variability in material found within the bracket of “bioplastics” adds layers of complexity to the task of trying to successfully recycle them (Lamberti, *et al.* 2020). Individual bioplastics have specific optimal methods of recycling (Lamberti, *et al.* 2020). Bio-PET is most effectively recycled by glycolysis, PLA by alcoholysis, bio-PE by pyrolysis (Lamberti, *et al.* 2020). Unless these specific bioplastics can be sufficiently sorted and processed to their unique specifications, they may merely complicate current recycling streams and contribute to more plastic waste in the process.

3.3 New sustainable alternatives need accurate and functional labelling

The nuances in the sustainability of new materials such as bioplastics and other sustainable plastic alternatives, must be effectively communicated to consumers. A material such as PLA being labelled as “compostable” is misleading to the end user as it fails to indicate that the material requires industrial bioprocessing, and that the infrastructure required for this may not be available in their region. Without this information a consumer is unable to execute the sustainable disposal method which is the basis for these materials being sustainable alternatives.

Effective labelling should accurately communicate the most “sustainable” method of disposal, based on the region of purchase, which more accurately reflects the sustainability of purchasing the product. Such labelling would more clearly reflect the suitable handling of waste, and inform consumers whether such “sustainable” use and disposal is possible depending on regionally available infrastructure.

4. Additives

4.1 Not just a polymer – An array of plastic additives

Additives are inorganic or organic chemicals added into polymer formulations during production to improve their performance, functionality, and aging properties. They include chemicals that act as plasticisers, flame-retardants, light and heat stabilisers, anti-oxidants, lubricants and pigments (Hahladakis et al. 2018). While the addition of chemical additives to a polymer improves the performance of the product, concerns arise as some of these are known toxicants providing pathways for human and environmental exposure (Hahladakis et al. 2018). Leaching is particularly a concern for additives which are not chemically bound to the polymer (Marklund, et al. 2003).

Limited data exists on human and environmental health effects from exposure to these chemicals, and for the majority of these chemical additives, health risks are still widely unknown (Galloway, 2015; Muncke, *et al.* 2020). A summary of additive groups and potential human health impacts can be found in Table 2.

Table 2: A summary of the range in plastic additives (including: Plasticisers, Bisphenols, Organic flame retardants, UV stabilisers, Metals, and Monomers & unknowns), rationale for their use, examples of specific types and their potential health impacts.

Additive group	Additive use	Examples	Potential health impacts
***Plasticisers* [a]**	*Manipulate flexability, ductability and toughness*	*Phthalates*	*Negative reproductive outcomes, oxidative stress damage, neurobehavioural disorders*
***Bisphenols* [b]**	*Intermediate in production of polycarbonates and epoxy resins*	*Bisphenol A, S, F, B and AF*	*Endocrine disruption*
***Organic flame retardants* [c]**	*Undergo competing reactions in the presence of fire to slow spread*	*Polybrominated diphenyl ethers, hexabromocyclododecane, tetrabromobisphenol, chlorinated paraffins and organophosphate esters*	*Diabetes, neurobehavioural and developmental disorders, cancer, reproductive health effects and alterated thyroid function*
***UV stabilisers* [d]**	*Mitigate polymer photooxidation, increasing durability*	*Benzophenone*	*Endocrine disruption*
***Metals* [e]**	*Production catalysts, biocides, pigments, light and heat stabilisers and flame retardants*	*Iron, zinc, copper, nickel, chromium and lead*	*Kidney damage, developmental disruption*
***Monomers & unknowns* [f]**	*None, these are unreacted monomers of the polymer and non-intentionally added substances*	*Bisphenols, styrene, vinyl chloride, and poly and per-fluorinated alkyl substances*	*Irritation and neurological impairment (styrene). Negative affects to developmental, immune and endocrine functions (PFAS).*

[a]Huang et al. 2020; Pérez-Albaladejo et al. 2020; Radke et al. 2018; Wei, et al. 2019. [b]Bittner, 2014; Tang, 2020. [c]Blum, et al. 2019; Doherty et al. 2019; Rauert, et al. 2018. [d]IARC, 2013; Medina-Perez et al. 2020. [e]Huerta-Pujol, 2010; Järup, 2003; Turner, 2016. [f]Arvanitoyannis and Bosnea, 2004; Hahladakis et al. 2018; Vera, 2018.

There is a plethora of additives used in plastic production, multiple groups with inter- and intra-variability in properties (Table 2) (Hahladakis, *et al.* 2018). Further to intentionally incorporated additives, there are also unreacted monomers and thousands of chemicals that are "unknown" or non-intentionally added substances (NIAS). Unreacted monomers from polymer production (Table 2) can migrate into food from packaging materials. Chlorine emissions from PVC plastics have been reported around 40%–56% Cl in PVC bags (Alam, 2018). The presence of NIAS is of significant concern, with Vera et al. (2018) reporting that of 58 of the 76 compounds identified in 26 PP films and food contact materials were NIAS. In addition, Gomez Ramos et al. (2019) and Bauer et al. (2019) identified a total of 52 NIAS migrants from food pouches purchased from markets in Spain, Australia, and Germany.

Adding to the burden of unknown chemicals are chemicals that have sorbed or migrated to the plastic material from other sources, providing the opportunity for further global transportation, e.g. through marine microplastics (Avio, 2015; Mato, 2001). One example is poly and per-fluorinated alkyl substances (PFAS), which are widely used in water/grease-proof food packaging products with potential to leach into food (Akhbarizadeh, 2020). They have also been detected in plastic water bottles, thought to originate from the ink of the plastic labelling and the additives used during plastic manufacturing (Llorca, 2012; Schwanz, 2016).

4.2 A complex issue, with many unknowns

Due to the broad chemical space that plastic additives occupy (in addition to NIAS and sorbed chemicals), there is immense difficulty in understanding the short- and long-term toxicological risks of different plastic types to human health and the environment (Galloway, 2015; Thomson, *et al.* 2010). Furthermore, as the global production of additive containing plastics continues with all these unknowns inadequately addressed, the concept of toxicity debt (acknowledging potential lag-time to toxic effects as pollution continues) highlights the potential risk to human health and the environment is only increasing over time (Rillig, *et al.* 2021).

Plastic materials present a potential “cocktail” of known and unknown chemicals, and the combined risk of these mixtures is poorly understood; the toxicological risk of mixtures is uncertain even when mixture composition is known (Kienzler, *et al.* 2010). A lack of information exists on where, how, why and in what quantities chemicals are used in the plastic manufacturing process. Without this information being provided by the manufacturer, accurate risk assessments cannot be carried out towards environmental and human health outcomes. Due to legislative and privacy-based restrictions imposed by industry, toxicologists are left to use crude estimates due to a lack of transparency. It is apparent that additive composition should be made clearer to the consumer and/or purchaser, and plastic manufacturers should be held more accountable for the composition of their product.

5. Concluding recommendations

The issue of plastic waste is more complex than indicated by contemporary labelling schemes (Figure 4a). As production rates increase, and the development of new materials and additives continues, communicating accurate information to consumers has never been more important.

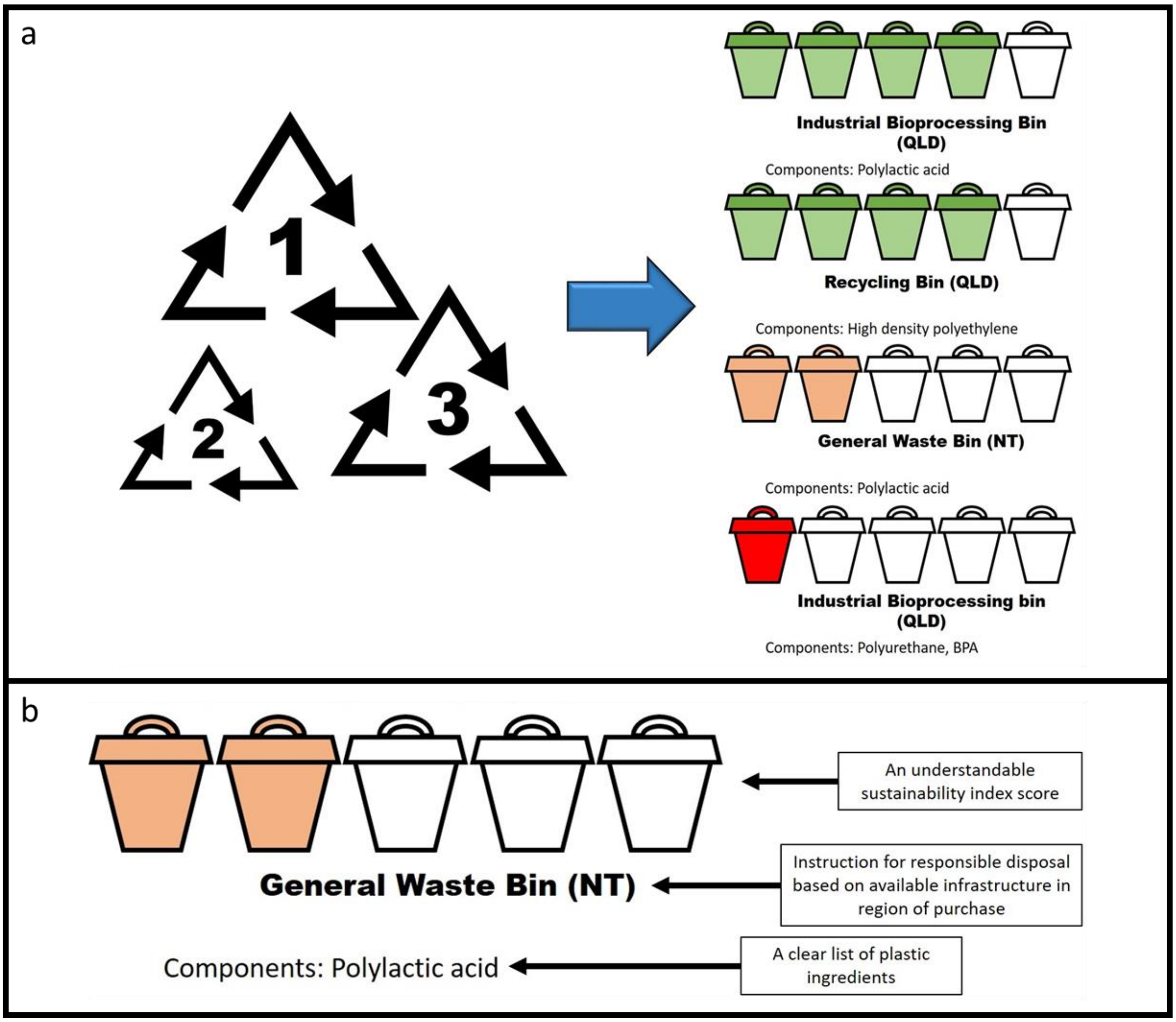

***Figure 4** – **a.** Moving away from limited, abstract, and categorical labelling schemes focused on recyclability to more detailed, regionally dependent, and scalable labels to facilitate more sustainable consumer choice. **b.** A visual concept based on the recommendations in this manuscript including: a clear indication of the plastic components, an instruction for responsible disposal based on the infrastructure available in the region of purchase, and a clear and understandable sustainability index score (based on above outlined factors such as, product lifespan, additive content, and availability of sustainable processing in region of purchase).*

Building on the discussion in this review, we have three main recommendations on plastic labelling:

1. Plastic labels should include **an understandable "sustainability scale"** to enable consumers to make informed decisions on the environmental and human health considerations related to plastic use (Figure 4b). We suggest the recyclability of plastic items is too complex for categorical recycling labels. The recyclability of a plastic item does not wholly determine how sustainable an item is when additive content, regional availability of disposal infrastructure and environmental cost of production are all factored in.

2. Plastic labelling should use **direct instructions appropriate for the region of purchase** (e.g. PLA could have an "Industrial Bioprocessing Bin" instruction in Queensland Australia, but a "General Waste Bin" instruction in the Northern Territory Australia) (Figure 4b). Categorising plastic items with broad and confounding nomenclature causes confusion over how materials can be responsibly disposed of and hence we suggest plastic labelling should disregard generic words like "biodegradable" and "compostable".

3. Plastic labelling should include **a legible list of additive components**, so consumers can make informed decisions on the plastic additives they are willing to expose themselves and potentially the environment to (Figure 4b).

These recommendations and the accompanying visual concept are not to be taken as exact instructions for international application; the issue of plastic waste management is one with significant regional variability. These recommendations are rather a guide for discussion around improving plastic labelling to better facilitate sustainable use, e.g. by local policy makers (in government and industry), with regional experience and understanding, to drive change in current, inadequate labelling schemes.

The difficulty in actioning these recommendations cannot be understated, as it will require cooperation between government, industry, the scientific community, and the public. We suggest this kind of cooperation is key to tackling such global challenges as plastic waste. The difficulty in this challenge is not sufficient reason for inaction. Labelling schemes will not solve excessive waste issues entirely, but if we are to stem the flow of plastic in the environment, the solution must be holistic in nature, including better communication of accurate information to the public.

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