Status quo and sector readiness for (bio)plastic food and beverage packaging in the 4IR

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Single-use plastics emanating from the food and beverage industry are polluting the environment, and there is increasing public pressure to find 'green' solutions to plastic pollution. The introduction of more bio-based and biodegradable plastics (possibly manufactured by disruptive technologies), increased plastic recycling, and enhanced degradation of plastics (micro, meso, and macro) in the environment can holistically contribute to solving the problem for future generations. In order to inform future research, it is imperative that robust background data and information are available. This review provides details about the volumes and categories of food and beverage packaging manufactured and recycled, and available data (qualitative and quantitative) on environmental plastic pollution in South Africa, and to a lesser extent, in Europe and globally. In addition, current and future trends and technologies for recycling, enhanced degradation, and manufacturing of plastics are discussed, with an emphasis on the manufacture of bioplastics.

Significance:

Plastic pollution needs to be tackled through a holistic combination of reduced use, enhanced recycling efforts, public education about littering, replacement of selected conventional plastics by degradable alternatives, and enhanced degradation of plastics in the environment.

Introduction

Plastic pollution of aquatic (marine and freshwater) and land environments has reached alarming levels over the last two decades. In addition, conventional plastics are manufactured from fossil fuels, thus exacerbating the environmental burden.[1] It is therefore imperative that alternatives to recalcitrant single-use petroleum-based plastics are introduced. This paper presents the results of a critical survey conducted by a group of researchers from South African academic institutions forming part of the Technological Higher Education Network of South Africa (THENSA) sub-group on waste management and the circular economy, as well as this sub-groups' Irish research partners. This review is aimed at academics, the private sector, and investors engaged in research, manufacturing and use of plastic food and beverage (F&B) packaging, with an emphasis on bioplastics. It provides information on the status quo of plastic use by the F&B industry in South Africa and identify gaps in the knowledge required to successfully reduce the impact of plastics on the environment. In some cases (for example, plastic production data, recycling data), the situation in South Africa is compared with that in the European Union as an example of the current situations in developing versus developed countries. The way forward in terms of plastics manufacturing is discussed in detail in the context of the Fourth Industrial Revolution (4IR).

The information was obtained from literature, as well as from the opinions of contributing experts from academic institutions, business and industry. A bottom-up approach was adopted to synthesise the most relevant details from the abundance of information available on this topical issue:

1. The volumes and categories of plastic F&B packaging manufactured in South Africa were obtained.
2. Qualitative and quantitative data from articles detailing plastic pollution of land and aquatic (freshwater and marine) environments in South Africa were collated.
3. The categories of bioplastics (Groups I, II, III, IV) and mechanisms (recycling vs enhanced degradation) that could be harnessed to lessen the environmental burden of the most widely used, as well as the most widely polluting F&B industry plastics, were critically assessed, and gaps in knowledge were identified.
4. Furthermore, innovations that have taken place in the manufacture of the identified F&B packaging over the last decade, as well as sector readiness for the 4IR, are highlighted.

Due to the considerable scope of the topic, an in-depth discussion on the synthesis and types of plastic polymers and biopolymers is not included in this review.

Classification of plastics/bioplastics

The terminology and classification of 'bioplastics' is rather complex (Figure 1) and covers an array of plastic polymers that are either biodegradable (and/or compostable), and/or manufactured from bio-based feedstocks.[2] To lessen confusion, differentiation of bioplastics into 'bio-based', 'compostable' and/or 'biodegradable' plastics is gaining traction. Plastics such as polyethylene (PE) and polyethylene terephthalate (PET) are recalcitrant to degradation and, unlike biodegradable and/or compostable plastics, are well-suited to recycling. They are classed as conventional (Group I) plastics when manufactured from fossil fuel feedstocks.[2] However, when manufactured from biological feedstocks (agricultural biomass, microbial biomass or microbial products), the term 'bio-based' (bio)plastic applies (Group II). The Group III polymers such as polylactic acid (PLA) and polyhydroxyalkanoate (PHA) are manufactured from bio-based feedstocks and are compostable. Group IV polymers such as polycaprolactone (PCL) and polybutylene adipate (PBAT) are manufactured from fossil fuels, but are still typically viewed as bioplastics because they are biodegradable and compostable.[2]

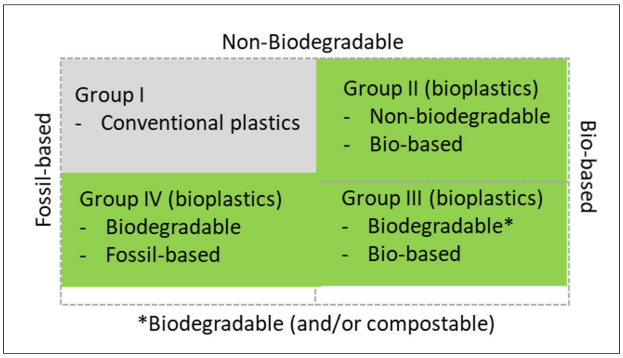


Figure 1: Basic classification of plastics and bioplastics (adapted from Jariyasakoolroj et al.[2]).

Plastics in the food and beverage industry

Food and beverage packaging assists in containing, preserving and protecting the contents during storage and transport.[3] Desirable qualities for F&B plastics include lightweight, durability, chemical resistance, cost-effectiveness, and manufacturing simplicity.[3] Historically, plastics were selected by the F&B industry chiefly on a 'fit-for-purpose' basis using these criteria.[1] However, with the alarming increase in environmental pollution over the past decades, the recyclability and/or biodegradability of single-use plastics has also become a critical consideration[1], and plastic selection should involve a cradle-to-grave approach[4].

Data on the quantities, types, and uses of plastics that are manufactured in South Africa were provided by industry (Plastix 911 2020, written communication, 28 July) (Figure 2, Table 1) and compared with data from Europe. Almost 40% of the 62.8 million tons of plastics manufactured in Europe in 2018 was used in general packaging.[5] In contrast, only around 1.5 million tons of polymer were converted into plastic products in South Africa in 2019, with almost half being used as packaging material, either rigid (60%) or flexible (40%) in nature (Figure 2). Approximately 70% (over 0.5 million tons) of the South African packaging was used by the F&B industry, but in order to arrive at the total annual sum, it was estimated that imported packaged F&B could add ≥50% to these figures (Plastix 911).

The most popular plastics used by the European F&B industry were polypropylene (PP), low-density polyethylene and linear low-density polyethylene (LDPE and LLDPE), and PET at 19.3%, 17.5% and 7.4%, respectively.[5] This differs somewhat from the landscape in South Africa, where estimated amounts were 35% PET, 33% LDPE/LLDPE, 12% high-density polyethylene (HDPE) and 11% PP in 2019 (Plastix 911).

Only 4 of the 13 main polymers that are manufactured in South Africa do not have current applications in the F&B industry (Plastix 911). These are rigid acrylonitrile butadiene styrene (ABS), styrene acrylonitrile resin (SAN), and the flexible polyester and thermoplastic polyurethanes (PUR and TPU). Many of the conventional plastic polymers are manufactured in both flexible and rigid forms (Figure 2), while others are only flexible [nylon, polyester polyurethane (PUR), thermoplastic polyurethane (TPU)] or rigid [ABS, SAN, PET, polystyrene (PS)].

There are a multitude of uses for plastics in the F&B industry (Table 1). As recycling rates of plastics such as PET are already high and set to increase (refer to the section on recycling for details), it is recommended that greater research efforts are directed into low value biodegradable and/or compostable alternatives for plastics that do not lend themselves to recycling and are more likely to litter the environment. For example, clingfilm that is capable of rapid and complete degradation in a variety of environments (including landfill sites) to replace the almost 10 000 tons of polyvinyl chloride (PVC)-based film used annually by the South African F&B industry (Table 1).

Plastic pollution

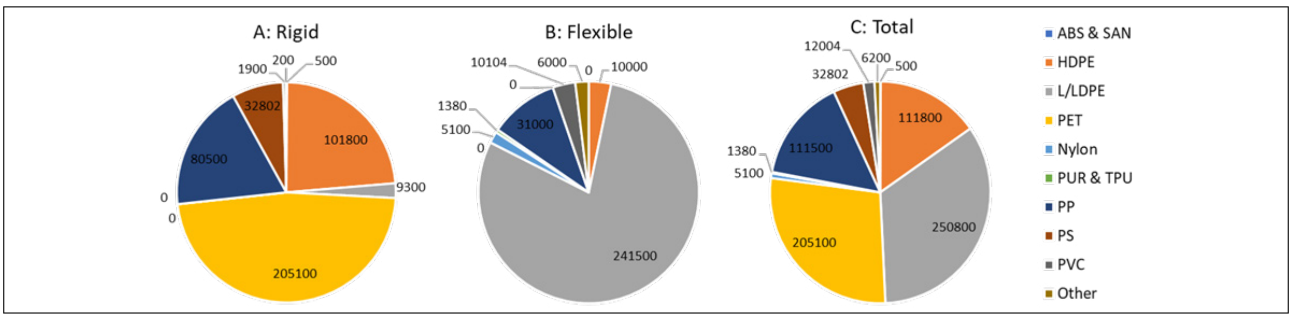
Quantification in the environment

In Europe, close to 60% of plastic waste is in the form of packaging, and the demand for plastic for F&B packaging was estimated to be 8.2 million MT in 2017.[3] Because oceans are downstream of land areas, they are the final sinks of much of the plastic waste generated on land.[6] A comprehensive study conducted in 2017 estimated that 80% of ocean plastic emanates directly from land-based sources.[6] Up to 77% of denser polymers such as PET and acrylics migrate to the sea floor in deep waters, while lower density polymers like PS foam, PE and PP generally float on the sea surface.[7]

Over the decades, plastics in macro (>25 mm), meso (5–25 mm) and micro (<5 mm) forms have accumulated ubiquitously and caused ecosystem stresses in marine, freshwater, and land environments.[8,9]

The current usage of plastic in South Africa is between 30 kg and 50 kg·per person·per year, which is significantly lower when compared to Europe (139 kg/person/year).[10] In total, 22 studies have been conducted since 2015 to determine the extent of plastic pollution in South Africa. Of these studies, 14 focused on abiotic environments (Table 2), and the rest focused on determining biotic accumulation (not included in this review). Only one land-based inland study was conducted[11], whereby macroplastic litter distribution in the shoreline around the Nandoni reservoir in Limpopo was quantified. Most of the litter consisted of F&B packaging, such as wrappers, bottle caps and beverage bottles, as well as plastic bags. In terms of item numbers, PP, PVC, PET and HDPE were the most abundant polymers, with PP constituting >45% by the number of items counted, but PET or HDPE accounted for most of the polymer by weight.

Weideman and co-workers[12] counted floating forms of macroplastic litter by visual observation from bridges spanning major rivers, and definitively identified 20% to be F&B packaging, 6% bottles or bottle tops, and 21% bags or packets. The origin of some of the other items could not be established (24% miscellaneous, 13% PS pieces), but it may also have been the F&B industry. The same authors[12,13] also determined that >98% of the items >0.025 mm filtered from bulk river and dam waters from the Orange–Vaal systems were microfibres. They established that



Data source: Plastix 911 (personal communication, 28 July 2020)

ABS, acrylonitrile butadiene styrene; SAN, styrene acrylonitrile resin; HDPE, high density polyethylene L/LDPE, linear low-density and low-density polyethylene; PET, polyethylene terephthalate; PUR, polyester polyurethane; TPU, thermoplastic polyurethane; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; Other, proprietary Surlyn™ and E/VAL™

Figure 2: Quantities of plastics manufactured in South Africa in 2019 (all figures in metric tons per annum).

Table 1: Quantities, products and applications of plastics used by the food and beverage (F&B) industry in South Africa in 2019

Polymer	Total (tons per annum, TPA)	F&B (%TPA)	Products, and %TPA and applications for each product
RIGID PLASTICS			
HDPE	101 800	55	Bottles and closures for dairy products, fruit juices, powdered goods such as hot chocolate, custard (32%); crates for bread, milk, soft drinks, beer, fresh produce **(14%); drums >5 L for edible oils and vinegar **(9%)
L/LDPE	9300	10	Caps and closures, peel-off lids
PET	205 100	87	Beverage bottles for carbonated soft drinks, still and sparkling water, energy drinks etc. (75%); bottles and jars for honey, peanut butter, mayonnaise etc. **(7%); sheeting for thermoformed packaging for fresh produce, meat and dairy products, sandwiches, chocolates, prepared meals etc. **(5%)
PP	80 500	40	Closures for beverage and water bottles (4%); buckets for yoghurt, nuts, chocolates, edible oils, shea butter, bulk ice-cream (5%); tubs and jars for yoghurt, margarine, dairy products, prepared spreads, spices, ice-cream (27%); drinking straws, coffee stirrers, cutlery, take-away food containers, re-usable cake domes (4%)
PS	32 802	92	Vending cups (6%); sheeting for thermoformed products – portion packs for yoghurts and condiments (16%); extrusion gassed sheeting for thermoformed packaging for take-away food containers, flat sheeting under cakes, pizzas etc., fresh produce trays e.g. mushrooms, trays for in-store packed meat and chicken, trays/containers for prepared meals etc. (70%)
PVC	1900	20	Sheeting for thermoformed products and die-cut display packaging (20%)
Other	200	90	Polycarbonates in water-fountain refillable bottles, epoxy lining in steel packaging (90%)
FLEXIBLE PLASTICS			
HDPE	10 000	60**	Thin barrier bags for fresh produce and cereal inner bags (60%)**
L/LDPE	241 500	70	Bags for frozen vegetables, milk, dry foods (rice, lentils etc.); co-extrusion laminates in barrier packaging for meat and dairy; laminates on paper and board for wettability and sealing
Nylon	5100	80	Co-extrusion layer in barrier films for meat, protein, and dairy products
PP	31 000	76	Biaxially oriented PP for confectionary, sweets, crisps, and chocolate wrappers, laminates for barrier films for food applications (36%); cast film and extrusion blown films for fresh produce such as tomatoes and bananas; laminates on paper and board for improved barrier properties and wettability (40%)
PVC	10 104	90	Industrial cling-wrap for in-store packing of meat, fresh produce, take-away meals etc. (90%)
Other	6000	90	Surlyn co-extrusion layer in form-fill and seal packaging for sweets, cereal and chocolates; E/VAL in co-extrusion layer in barrier films for spices, coffee/cappuccino sachets; E/VAL in packs for ready-to-eat sauces, soups etc.; E/VAL co-extrusion layer in refill pouches for custard, baking powder, beverage concentrates etc.

HDPE, high density polyethylene; L/LDPE, linear low-density and low-density polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; Other, proprietary Surlyn™ and E/VAL™

***Estimate of HDPE for bags, crates, and drums and PET for bottles, jars, and thermoformed packaging (estimated % split between F&B and other industries).*

larger plastic items and microplastics composed of denser polymers were less likely to be washed out to sea, and more likely to become entrained in dams and riverbanks than the lighter and/or smaller items, particularly microfibres. It has been established that marine microfibres do not typically emanate from F&B packaging, but are composed of plastic from washing synthetic clothing, disintegration of maritime ropes and nets, and degradation of cellulose acetate in cigarette butts.[14,15]

The accumulation of microplastics in sediments is influenced by a number of factors, including the composition, size and shape of the microplastic, the type of sediment, the amount of organic matter in the sediment, the water depth, the flow rate, and the presence of barriers such as weirs or dams.[13,14,16] Chitaka and Blottniz[17] surveyed litter accumulation on five Cape Town beaches and found that of the 2961 litter items per·day per 100, 94.5–98.9% were composed of plastic, and 40–60% of these were F&B packaging, most being snack packets and single sweet wrappers.

Microplastics have been quantified in African beach sediments[15,18], surf-zone water, and open coastlines[18]. Similarly, seafloor macroplastic litter[19] and marine microplastic accumulation[20,21] have been quantified. None of these studies provided insight into specific land-based human littering behaviour, but other studies[22,23] have found that microplastic pollution in more densely populated areas such as harbours and/or urban estuaries was due to land-based litter inputs. In terms of composition, Vilakati and co-workers[24] established that microplastic fragments found on seashores around Cape Town were composed of PE, PET, PVC, PS, polyamide, polyacrylic acid, and ethyl vinyl acetate, with PE>PET>PVC being the most prevalent (Table 1). It is clear that most South African studies (Table 1) have been conducted on microplastic contamination of coastal aquatic and marine environments. In order to inform the type of F&B packing that should be earmarked for research, studies are required to obtain more land-based and inland aquatic litter data.

Reducing the environmental impact of plastics through legislation and innovation

Plastic recycling

It is estimated that 4900 Mt of the global 6300 Mt of plastics ever produced up until 2017 was discarded, with only 567 Mt (9%) being recycled.[25] The global mechanical recycling rate of plastic waste was estimated to be between 14% and 18% in 2017.[26] South Africa has a relatively well-developed and growing plastic recycling industry, with a higher input recycling rate (46.3%) than Europe (31.1%).[5,27]

The success of plastic recycling in any country or region depends on strong government policies that are well implemented, the availability

Table 2: Selected data from studies conducted to determine plastic pollution in South Africa and the surrounding marine environment

Location	Environmental (abiotic) site	Size and/or type of polymer	Quantification	Reference
Nandoni Dam, Limpopo	Populated shorelines	Macroplastic / PP > PVC, PS, PET, HDPE	~10 to 45 plastic items/25 m^2, ~40–700 gdwt plastic/25 m^2 (n=4 sites)	11
Orange–Vaal River system	Surface river water	Microplastic (>0.3 mm), Macroplastics (see text)	Wet season: 0.38±1.06 items/m^2 (n=18 sites) Dry season: 0.27±0.69 items/m^2 (n=9 sites)	12
Orange–Vaal River system	Dam river water	Microplastic / hard (85%), flexible (9%) PS (3%)	0.046±0.166 items/m^2 (n=5 dams)	13
Eastern Cape	River sediments	Microplastic / ND	6.3±4.3 (summer), 160±140 (winter) particles/kg (n=21 sites)	14
South African coast	Beach sediments	Microfibres (< 1mm)	33–127 microfibres/dm^3 (n=175 sites)	15
Braamfontein Spruit	Stream water, sediments	Microplastic / ND	Stream water: 705 particles/kg dwt Sediments: 167 particles/kg dwt	16
Cape Town	Beaches	Litter (94.5–98.9% macroplastic) / ND	134 (Muizenberg) to 4421 (Paarden Island) g/day/100 m (n=5 sites)	17
SE coast	Beach sediments, surf-zone water	Microplastic / ND	Beach sediments: 689±348 to 3308±1449 particles/m^2 Water column: 257.9±53.36 to 1215±276.7 particles/m^3 (n=21 sites) Harbour water columns: 413±78 to 1200±133 particles/m^3	18,22
Sub-Saharan Africa	Seafloor of continental shelf	Macroplastic	Seafloor litter: 0.2 to 2.1 items/km^2	19
KwaZulu-Natal	Sea-surface of coastal shelf	Microplastics / PS, other polymers ND	3.0±2.9 (summer), 5.5±3.3 (winter) particles/100 m^2	20
Atlantic Ocean	Sub-surface water	Microplastic / PE, PA, acrylic–PA blends	1.15±1.45 particles/m^3, PE (49%), PA & acrylic–PA blends (43%)	21
KwaZulu-Natal	Beach and estuarine sediments, surface water	Microplastic / PS, other polymers ND	Sediments: 3.7±5.6 to 160±271 (estuarine), 20±10 to 745±130 (beach) particles/500 mL Surface water: 10±11 to 70±119 particles/103 L	23
Cape Town	Seashore	Microplastics / PE, PET, PVC, PS, PA, PAA, EVA	PE prevalence: 87.5% (n=6 of 7 locations) PET prevalence: 71.4% (n=5 of 7 locations) PVC prevalence: 57.1% (n=4 of 7 locations)	24

ND, not determined; dwt, dry weight; PP, polypropylene; PVC, polyvinyl chloride; PS, polystyrene; PET, polyethylene terephthalate; HDPE, high density polyethylene; PE, polyethylene; PA, polyamide; PAA, polyacrylic acid; EVA, ethyl vinyl acetate

of infrastructure, and, most importantly, industry and community participation. Globally, governments are constantly considering new policy interventions to cut down plastic production, and to reuse and recycle non-degradable plastics. A number of international and South African agreements, policies, and strategies are collectively geared towards reducing plastic pollution by increasing the demand for recycled plastics and improving waste management to reduce or eliminate plastic waste at source.

South Africa's *Waste Act of 2008*[28] stipulates that waste should be separated at household level, and the respective municipal waste collection services should support the waste collection practices. The South African target for recycling is 70%, with the average plastic content of all plastic goods targeted at 30%.[10,27] Specific 5-year targets for reuse, collection and recycling of different forms of F&B plastic packaging have been set in the South African extended producer responsibility regulations. For example, recycling of PET has been set as 54% in year 1 with a stipulated increase to 65% by year 5. In the European Union, the strategy for plastics in the circular economy was adopted in 2018 and ambitious targets are set with a 55% recycling target for plastic packaging by 2030.[5,29]

The key steps in recycling plastic waste into secondary raw materials include collection, sorting, pre-treatment, decontamination and reprocessing.[30] The type of polymer, the ultimate application, the presence of other materials and additives (e.g. caps, coatings, adhesives and inks), the presence of impurities (e.g. dirt/soil/dust and organic residues), and the degree of service-life degradation are all factors that can impact on the suitability of plastic waste for recycling.[31]

The collection and sorting processes for plastic waste vary amongst regions, countries and cultures.[32] A formal collection system and advanced waste management infrastructure exists in the Global North, while in many developing countries like South Africa, waste recycling is less controlled.[33] Nearly 34% of the South African population did not have access to regular waste removal in 2016, and most of the recycling took place within metropoles, with only 3% taking place in rural areas.[34] Collection of plastic waste by the informal sector (waste 'pickers') in South Africa is an important conduit for waste recycling, but is selective in nature because it depends on trade prices and fluctuations in the demand for specific plastic types (mostly higher weight PET, HDPE and PP items).

Sorting of plastic waste is a key factor in recycling as it ultimately controls the quality of the material that will be transported (in bales) to reprocessing sites. Depending on the context (developed vs developing countries) and the origin of the waste, sorting takes place in material recovery facilities, plastic recovery facilities, sorting centres and/or reprocessing facilities.[33] In most countries, including developing countries like South Africa, sorting is manual. However, in some parts of Europe, near-infrared technology is employed, which is more technologically advanced but suffers from some limitations. Near-infrared sensors 'read' only what they can detect, and so false readings may occur, resulting in incorrect sorting when a product is composed of more than one type of plastic, or mixed with non-polymer material/s. The sensors are also blind to 'carbon black' and cannot detect material such as black PET, eliminating it from the recycling lot.[33]

To guarantee high purity levels of sorted plastic, especially for high value polymers such as clear PET and HDPE, near-infrared technology is often paired with other physical sorting processes (e.g sink-float, hydrocyclone)[35], or, in some cases, with manual sorting. In less advanced facilities, 13–18% of target plastic may be rejected during sorting, with another 12–15% lost due to non-target plastics being discarded.[35]

The recycling lot can be composed of multilayered plastics, flexible plastics (films and bags), black plastics and bio-based plastics, each of which has an associated sorting challenge.[36] It is generally not economically viable to segregate multilayer plastic components, nor plastic film. The latter can account for 40–50% of plastic waste in developed countries, but their low bulk density leads to technical difficulties during sorting and mechanical reprocessing.[31] Bio-based plastics which are identical to their petrochemical-based counterparts, such as bio-PE and bio-PET, can be used as 'drop-in' materials, and therefore can be easily integrated into existing sorting systems. However, contamination of segregated polymer streams with compostable and/or oxo-degradable plastics can compromise the quality of the recyclates[31,33], requiring adaptation of sorting equipment.

Enhanced degradation of plastics

Photodegradation, thermo-oxidative degradation, hydrolytic degradation, chemical degradation and biodegradation are the main mechanisms by which plastics degrade in the environment. Composting is a form of enhanced biodegradation. Some compostable plastics can be home composted, while others require more extreme conditions only achievable in industrial plastic composting facilities.[4] Under natural conditions, depending on the type of plastics, the degradation process can be extremely slow. Plastic degradation, by which polymers are fragmented into smaller molecules or elements through hydrolysis or photo/thermo-degradation can be enhanced, for example, by altering reaction conditions or including additives in the polymer mix.[37] These degradation processes and rates are largely incumbent on the type of polymer. For example, studies have demonstrated that: (1) the rate of hydrolysis of PLA and poly(3-hydroxybutyrate) (PHB) can be expedited at higher temperatures and/or pH[38,39], (2) the degradation of PP, HDPE, and LDPE can be promoted by pre-treatment at 80 °C[40], (3) clay additives promote diffusion of water into PLA/clay nanocomposites, thereby enhancing PLA degradation rates[41], (4) addition of 50% ethanol can accelerate PLA hydrolysis[42], (5) nanomaterials such as zinc oxide (ZnO) can be used as natural catalysts to enhance the degradation of polymers[43], and (6) photosensitive polymer additives such as titanium dioxide (TiO_2) and ZnO can accelerate photolytic activity associated with light wavelengths from 200 nm to 700 nm [e.g. the photolysis of polybutylene succinate (PBS) by addition of TiO_2 nanoparticles)[44].

Some plasticised polymers such as PLA can be biodegraded into intermediate products and may be further degraded (mineralised) into water, carbon dioxide (CO_2), methane (CH_4) and other inorganic compounds by the action of microorganisms. Key to this biotechnological approach is microbial secretion of extracellular depolymerising enzymes that 'break' the polymers into small enough particles so that they can be internalised into microbial cells where they can be mineralised via microbial metabolic pathways.[37,45] Several microbes capable of degrading different types of polymers have been identified, including PLA biodegradation by *Fusarium verticillioides*, *Penicillium roquefort*, *Amycolatopsis* sp., *Bacillus brevis*, and *Rhizopus delemar*[37], and PHA degradation by a lipase produced by *Bacillus subtilis*[46]. Application of functional microbial consortia (i.e. a mixture of microbial strains with different metabolic capabilities) may result in higher degradation rates when compared to the use of single strains, as demonstrated by Pattanasuttichonlakul and co-workers[47] who used a consortium of *Actinomadura* and *Pseudomonas geniculate* to degrade PLA beverage cups.

The biodegradable characteristics of polymers can be manipulated by blending them with other biodegradable materials. For example, Masmoudi and co-workers[45] demonstrated that the biodegradation rate of starch reinforced with cellulose was faster than that of PLA/cellulose fibres. Depending on the longevity required for a particular application, different polymer composites can be used: for example, a starch–polymer composite with a relatively slow degradation rate would be appropriate for single-use F&B packaging. It is thought that the complete lack of functional groups on the extensive inert C-C backbones of conventional plastic polymers renders them recalcitrant to biodegradation. However, some studies have suggested that PE and PVC may be biodegradable, but the authors did not elucidate the enzymatic pathways.[48]

Much remains to be discovered about enhanced plastic biodegradation. Techniques such as protein engineering of enzymes, strain engineering, metagenomics and genome mining are currently being explored. Examples include (1) enhanced degradation of polyurethane by engineered cutinase and polyurethane enzymes[49], (2) the use of genetic engineering to enhance the activity of an enzyme derived from *Bacillus subtilis* for the degradation of PET[50], and (3) the use of metagenomic gene mining to discover plastic depolymerisation enzymes in marine and terrestrial microbial communities[51], and biofilms causing plastic fouling[52], including the discovery of a cutinase and a lipase from two strains of *Pseudomonas* that have been shown to be effective in polyester degradation[53].

Combined physical and/or chemical and biological approaches are also promising. Awasthi and co-workers[54] increased the rate of biodegradation of HDPE by *Klebsiella pneumoniae* by heating the polymer at 70°C for 10 days beforehand. Similarly, Tian and co-workers[55] increased the rate of biodegradation of PS by *Penicillium variabile* using ozonation as a form of pre-treatment. The challenge is now to apply the laboratory findings to the 'real world' in order to remediate our environment through enhanced plastic degradation.

Manufacturing of (bio)plastics for food and beverage packaging

Bioplastic manufacturing is an emerging and innovative industrial sector that involves the production and processing of biopolymers into biodegradable plastic products. The bio-based polymers can be extracted from biomass, synthesised through intermediaries, or produced by microorganisms. These processes have been well reviewed in the literature and are therefore not discussed in detail here.

Bio-based feedstocks

To reduce the volume of plastics made from fossil fuels, biological materials may be used to synthesise Group II or Group IV (bio-based) bioplastics.[2] Agri-industrial wastes are available in large quantities, making them ideal feedstocks for valorisation. The South African agri-industry generates thousands of tons of residues suitable for downstream bio-economic applications from the processing of millions of tons of sugar cane, grain crops, and fruit each year.[56,57] Feedstocks such as starch can be used to generate plastic polymers by direct chemical processes, while a number of organic feedstocks can be used as substrates for indirect microbial polymer production.[2,58] Some examples of food products and ancillary wastes containing oil, protein, cellulose, starch, hemicelluloses and lignin that can be used to make plastic polymers, either directly or indirectly, are provided in Table 3.

It is challenging to manufacture bio-based plastics with properties comparable with those of conventional plastics. For example, typical starch-based bioplastics have (undesirably) high water affinities and poor mechanical performance when compared to their conventional counterparts.[59] Examples of successful F&B bioplastics include renewable packaging materials from PLA or other bio-polyesters, and cellulose-based polymers sourced from de-lignified wood pulp or cotton linters for coated cellulose films for bread, fruit, meat, and dried product packaging.[60,61] Some cellulose-based polymers are transparent, have high tensile strength, and serve as alternatives to LDPE, HDPE, PS and PET for F&B packaging.[60-62]

Table 3: Examples of food wastes and agri-industrial wastes used to produce biopolymers (adapted from Sharmila et al.[58])

Substrate	Sources
Celluloses	Mango seeds, peanut husks, citrus peels, rice, and wheat straw
Lignin	Peanut husks, wheat straw, leaves and stalks of corn, sugar cane bagasse, and peels of citrus fruits
Fats and oils	Mango seeds, potato waste, peanut seeds, citrus peels, pulse processing waste, coconut waste, waste cooking oil, animal fats
Protein	Soybeans, sunflowers and peanuts; cereal by-products e.g. gluten from wheat and maize zein; animal tissues such as collagen, keratin, and gelatin

Conventional plastic manufacturing processes

Extrusion and blow moulding

Extrusion is the continuous plastifying, conveying and pushing out of thermoplastic material through specifically shaped dies to make continuous products such as piping, engineering profiles, films, or plates. The semi-finished products can be processed further by thermoforming, and foam extrudates can be produced by adding foaming agents. A way of improving the tensile strength and rigidity of extruded film is by in-line stretching after extrusion, as with biaxially oriented PLA film (BOPLA).[63] In addition, blow moulding can be combined with extrusion.

The most common types of blow moulding are extrusion blow moulding and stretch blow moulding. Beverage bottles have been made from bio-PE by blow moulding, and the Group IV bioplastic PLA is ideal for this process.[64]

Injection moulding

Injection moulding is the most frequently used form of plastic processing. Components with a variety of shapes and sizes can be inexpensively moulded in large quantities for direct usage. The plastic is melted and injected under high pressure into the mould in an injection moulding machine. Examples of injection-moulded plastics used by the F&B industry include disposable cutlery and beverage cases.[64]

Bio-based polymers can be used for injection moulding provided they have similar characteristics to conventional petroleum-based plastics. It is also common to blend bio- and fossil-based plastics (e.g. PLA with PBAT). Multi-component injection moulding is gaining in popularity with technical advancements in plastic moulding, with a recent study showing that it may be optimised for processing different recycled polymers in micro- and nano-layers.[65]

Thermoforming

Thermoforming as a manufacturing process uses a semi-finished flat plastic material to produce three-dimensional parts under hot, high-pressure air and vacuum. Typical F&B applications are yoghurt or margarine tubs and drinking cups, and the manufacture of bio-based containers for the packaging of ready-to-eat foods.[66]

Plastics and bioplastic manufacturing and recycling and 4IR

The 4IR is incumbent on a society that adheres to circular economy principles of creating resources instead of generating waste. The plastic industry is set to enter the 4IR using advanced technologies, including additive manufacturing, robots, drones, driverless vehicles, advanced Internet connections (the Internet of Things) and sensors, and decentralised forms of energy, while new technologies such as advanced robotic sorting and driverless collection vehicles may change the landscape of plastic waste management and recycling.[67]

Additive manufacturing

Additive manufacturing, commonly referred to as 3D printing, is a rapidly developing manufacturing technology that builds objects by sequentially depositing fine layers of material, including plastics, according to digital 3D-model data. It has been referred to as a disruptive technology that has the potential to fundamentally influence many processes. In addition to the potential of additive manufacturing to replace many conventional manufacturing processes, it has prospective impacts on the economy and society by promoting innovative business models, products and supply chains.[68-70]

Ribeiro and co-workers[71] recently reviewed data from life-cycle assessments and proposed a new framework for environmental, economic and social sustainability of additive manufacturing that takes into account different life-cycle phases, methods, technologies and materials. A study by Gebler and co workers[72] suggested that increased use of additive manufacturing could lead to a global energy saving of up to 5% by the manufacturing industry by 2025, but other researchers have contested the energy saving potential of additive manufacturing.[71,73]

In comparison to traditional plastics manufacturing methods, additive manufacturing can be used to fabricate more complex shapes in a more sustainable manner as little to no waste is generated; in addition, the technology lends itself to the use of biopolymers (particularly PLA) and bio-based feedstocks, furthering the 4IR ethos.[67] Additive manufacturing consists of three main phases: modelling, printing, and finishing. Five common techniques are applied for polymeric materials: material extrusion, material jetting, binder jetting, powder bed fusion and sheet lamination.[68] Technological challenges include difficulties with simultaneously printing different materials (e.g. metals with polymers), the lack of low-cost printable materials, and slow print times. Despite the perceived benefits of 3D printing, with the exception of the aerospace and biomedical (parts) industries, the technology has not yet been embraced for large-scale manufacturing, due to a number of limitations including lack of reliability and standardisation, issues with intellectual property, generally slow cycle times and the trade-off between scale and quality.[67,68,71,74] However, it has been widely adopted in the research arena because it is highly customisable and capable of printing complex geometries.[67,68,74]

Beyond 3D printing

Recent advancements in additive manufacturing have resulted in the creation of a new dimension in four-dimensional (4D) printing and 5-axis 3D printing to generate metamaterial structures with different superimposed structural responses initiated by changes in their operational environments. The applicable 4D printing methods include fused deposition modelling and stereolithography.[75] A major challenge faced by 4D printing is that the mechanical properties of 4D-printed structures may be restricted by the preferred shape and/or functionality of the product. For example, the polymer ratios are critical to sequential folding of the locker structures. The introduction of 'smart' printable materials and a deeper understanding of scale on the structure and function of (bio)plastic products are crucial to overcoming these challenges and advancing 4D printing.[75,76]

The impact of the 4IR on plastic recycling

New materials, advanced sensors, the Internet of Things, and robots are expected to revolutionise waste sorting and recycling of plastic materials. Albeit with low impact, robots and driverless cars are already being used by the waste industry.[77] Social media and mobile applications are expected to have a significant impact on connectivity amongst formal and informal recyclers. To fast track the new developments in plastic recycling and support the circular economy, innovations on fully robotic sorting and recycling plants, and reuse and redesign of products are considered to be the impacts with the greatest importance. The top six investment priorities to support and enable these are mobile apps, new sensors, social media, big data, new materials and digital utilities platforms.[78]

Conclusions

Pollution of the environment by single-use F&B packaging made from fossil fuels is of global concern. To mitigate environmental plastic pollution while promoting the principles of circular economies, packaging made from selected plastic polymers that are not readily degradable needs to be recycled, and bio-based and/or compostable/biodegradable plastics need to be introduced on a 'fit-for-purpose' basis. A robust plastics recycling industry exists in South Africa, with non-recyclables being the major contributor to environmental litter. Therefore, as a starting point, research and mitigation measures need to be directed at those plastics that do not form part of the recycling value chain in South Africa. Extended producer responsibility regulations have recently been promulgated and published in South Africa.[79] This legislation should theoretically translate into reduced use of plastics and increased recycling of plastics in South Africa.

From a cradle-to-grave perspective, waste minimisation and energy conservation extend to the manufacturing of plastics. Conventional plastics utilise fossil fuels as feedstocks, thereby contributing to the generation of greenhouse gases. Unfortunately, in most instances, plastics from renewable feedstocks are not comparable with their conventional counterparts in terms of mechanical properties and/or cost and/or recyclability. In the future, additive manufacturing, which has arguably been touted as generating less waste while using less energy, may 'disrupt' traditional plastics manufacturing processes. Together with constant improvements in plastics made from renewable resources, the plastic industry is set to enter the 4IR.

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Competing interests

We have no competing interests to declare.

Authors' contributions

P.J.W.: Project management; conceptualisation; writing – initial draft. L.Z.L.: Conceptualisation; writing – initial draft. P.M., S.K., G.D.A., A.R., C.C. and B.F.B.: Writing – initial draft.

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