Evaluation of new technologies to reduce plastic waste in Aotearoa New Zealand

Dr Cherie Tollemache

Intern project at the Office of the Prime Minister's Chief Science Advisor, completed April 2021

Note: These resources have not been peer-reviewed

This document aims to provide a detailed analysis of the technology and innovation that could help Aotearoa New Zealand move to more sustainable use of plastics to support the Ministry for the Environment in their prioritisation of innovation and research in this area, with a specific focus on relevance to and application in Aotearoa New Zealand. The technologies and innovations are segregated into the relevant areas of the plastic waste system: leakage prevention, recycling, alternative materials, environmental remediation, reuse and upcycling. Each section begins with a short statement on the potential impact of addressing the specific area of the waste hierarchy and summarises advantages and barriers that can be generally applied to all technologies within that section (where appropriate). This is followed by a detailed table that provides examples of the tech/innovation estimated costs, barriers for implementation in Aotearoa New Zealand and proposals of what could make it successful here. Each row also has a links and references column that can be referred to if more detailed information is required.

Summary of topics included

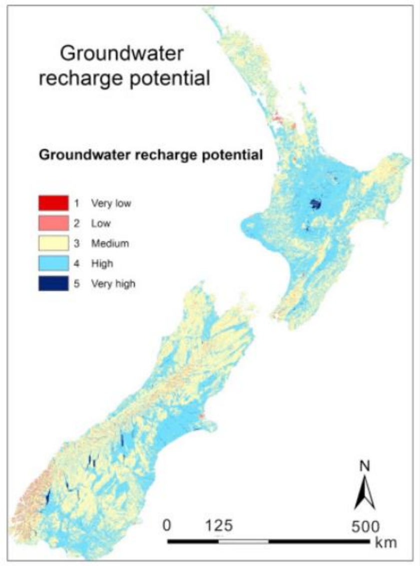
Leakage prevention technologies

Source prevention is likely to have the largest impact in reducing plastic to environment flows. Source prevention technologies do not currently address all sources of plastic pollution and have not been widely adopted. Perfect implementation of leakage prevention will not remove the need for environmental remediation due the enormous amount of plastic pollution that already exist and because leakage prevention cannot currently address all sources of plastic to environment leakage. Downstream leakage prevention measures (such as catchment in stormwater and wastewater flows) should also be considered. Wastewater treatment strategy selection should be influenced by the type of sewerage system – for example, combined wastewater and stormwater has different contaminants than the two separated streams. Wastewater treatment solutions can be more cost effective if other source leakage and capture technologies are implemented prior to the flow into the treatment facility.

Table 1: Plastic-to-environment leakage prevention technologies and innovations

Leakage source	Technology innovation	Specific examples/advances	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Laundering Textiles (microplastics)	Washing machine filters for household use (downstream capture)	Each filter retains 90 per cent of the microfibres generated during washing, according to the manufacturers. Filters must be replaced monthly. Environmental Enhancements Lint LUV-R filter installed outside of washing machine prevents textile microplastics to ocean (87%). Coraball – ball that gets placed into the washing machine, collects about 30% of MP fibres per wash cycle. PlanetCare makes consumer and industrial washing machine filters (90% filtration of microfibres). Guppyfriend: washing machine bag for washing synthetic fabrics captures 86% of microfibres (lasts 50 household washes before needing replacement).	Lint LUV-R filters USD 131 per year and per household. Cora ball $60-$120 per household (1 or two balls depending on washing machine size). PlanetCare filter €140 initial cost and €120/year for maintenance per household Guppyfriend €30 per bag. 2-5 per household per year.	It is not clear how to manage filter waste residue. Enforcing treatment solutions for microplastics at household level is viewed as expensive when end-of-pipe wastewater treatment systems can be envisaged.	For households: Approaches such as providing filters/coraball/guppyfriend when washing machines are purchased could support wide adoption. Coraball is a cheaper alternative for the household. The product is durable (lasts years) and NZ distributer already exists but is less effective than filters.	https://environmentalenhancements.com/store/index.php/products/products-lint-filter https://coraball.com/ https://planetcare.org/products/microfiber-filter
Laundering Textiles (microplastics)	Fabrics that don't shed microfibres (REPLACE, source prevention)	**Innovative and quality formulations of textiles Techniques.** Some manufacturing processes are known to affect releases of microfibres during textile washing. Effectively combining synthetic and natural textiles and eliminating loose (poor quality) fibres could help reduce fibre loss during washing by up to 80 per cent. **Textile coating** Use of silicon emulsion to coat textile fibres reduces fibre loss during washing. **Improved knitting techniques**. Tight knitting increases the concentration of fibres per area and the amounts of microfibres released during fabric washing. **Ultrasonic welding of fabrics**. This technique is better than conventional cutting techniques: reduction of fibre loss is 70% for particles larger than 5 µm in diameter.	??	Source prevention measures for textiles are less likely to be cost effective if a self-certification process is used to govern the implementation of maximum thresholds for fibre release. Capture at the washing machine may be more favourable.	The use of levies on fabrics and products that result in high microfibres release, in order to help finance higher treatment costs/subsidies on good replacement fabrics could be explored. Third party testing of textile products may be necessary to regulate thresholds of fibre release.	(Nikiema Josiane, Mateo-Sagasta Javier, Asiedu Zipporah, Dalia Saad Dalia, 2020)
Laundering Textiles (microplastics)	Treatment of effluent from industrial and commercial laundries	Methods for wastewater treatment that are reasonably well developed: **Precipitation/coagulation and flocculation Adsorption on granular-activated carbon (GAC).** **Membrane filtration (e.g. ultrafiltration and reverse osmosis).** Norlex Continuous inclined Separation System (CSS) 5 plants for industrial laundries in Sweden.	??	Infrastructure costs mean strategic placement would be necessary, industrial laundries that launder for specific industries should be targeted – which industries requires more data to determine (Swedish study suggests hospital laundry should be priority).	Some technologies exist for treating industrial laundries' effluents. In the past the focus of treatment was not the removal of microplastics, but rather the removal of oils and suspended solids. Adaptation of treatment units for microplastics may be more cost effective. Downstream WWTP fitted to tertiary treatment with microplastics in mind may be more appropriate solution for NZ.	(Norin & Ab, 2018) https://www.norlex.com/industrial-laundries-emit-tons-of-wastewater-every-day/

Leakage source	Technology innovation	Specific examples/advances	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Tyre abrasion (microplastics)	Tyre fixture for continuous collection of microplastics (capture at source)	The Tyre collective Collects microplastic shed from tyre. Particles under 50 microns are small enough to be reused in new tyre walls (closed loop). This capture technology is appealing because there is no incentive for tyre manufacturers to improve the abrasion rates of their products by developing tyre tread/material techs (source prevention strategy)	Not on market yet	Start-up is in scale up phase,	Electric vehicles (EV's) will lower tailpipe emissions, but tyre wear is projected to increase due to the added battery weight and torque. Govt promotion of switch to EV could come with scheme for collection of trye microplastics for re-treading tyres?	https://www.thetyrecollective.com/
Tyre abrasion (microplastics)	Porous asphalt Permeable pavement can have grass or gravel infilling. Can be manufactured from recycled plastic.	Netherlands has over 95% of its highways made from porous asphalt and 9% of their asphalt production is porous. Invisible structures - Grasspave[2] and Gravelpave[2] Turfstone UNI Eco-Stone Not new but should be widely adopted.	More expensive than impermeable asphalt. The cost associated can be saved in storm water treatment costs.	Some materials are prone to clogging usually (soil/grass filled systems are more susceptible). Once totally clogged, these systems have to be removed and replaced. Frequent replacement renders these types of systems impractical and expensive. Long-term performance not well-studied but generally agreed that effectiveness diminishes with time.	Implementing a charge on developers (storm water impact fees) which is waived when porous asphalt is used. Implementation of twice-yearly high-pressure cleaning of road shoulders to maintain permeability. In NZ, porous asphalt comes in a range of mixes, distinguished by variations in its particle size distribution. 2011 study of 4 Auckland roads (2 with porous asphalt and 2 chip seal roads) has confirmed the benefit of reduced suspended solids in road runoff (microplastics not separately evaluated).	https://www.invisiblestructures.com/products/gravelpave-2/ https://www.mutualmaterials.com/products/eco-stone/ (Moores, 2011; Nzta, 2011; Scholz & Grabowiecki, 2007)
Wastewater and urban runoff	Sustainable drainage systems (SuDS)	**Filter strips** **Dry swales** **Infiltration chambers** **Perforated pipe systems** This is really big in the UK. Includes retention ponds and wetlands (below). Benefits of SuDS extends beyond plastics/pollution control to flood risk management, biodiversity benefits.	The capital costs of SuDS solutions are lower than the capital costs of comparable conventional solutions **Filter strips:** **Investment cost:** the range of £2-4 per m2 filter strip area. **Operating cost:** regular maintenance of £0.10 per m2 of filter surface area per year **Swales:** **Investment cost:** £10-15 per m2. **Operating costs:** £0.10 per m2 of filter surface area per year **Infiltration chambers:** ?? **Perforated pipe systems:** low to no maintenance costs, higher investment cost compared to other SUDSs.	Key barrier to greater uptake of good quality, landscaped SuDS is uncertainty around adoption and ongoing operation and maintenance. Different SuDS schemes in different places have very different costs and benefits.	Retrofitting is more costly. Implementation in NZ should occur in new developments. SuDS are widely used in NZ but we have not previously considered their placement as a means for preventing plastic pollution. NZTA standard for state highway infrastructure (2010) does not consider plastic contaminants (no data). Updating this document to include plastic pollution?	(Schmaltz et al., 2020) https://www.susdrain.org/delivering-suds/using-suds/benefits-of-suds/SuDS-benefits.html https://www.susdrain.org/resources/evidence.html (Scientific evidence list cost/benefit etc) (Ashley et al., 2017) (Transport Agency, 2010)
Wastewater runoff (macro-plastics)	Wastewater runoff (before treatment plant, capture)	**Booms** Large scale booms in operation: Ocean Cleanup System, Holy Turtle Clean river project River Boom, Bandalong Boom, The Litterboom Project, AlphaMERS Floating Barrier, Plastic Fischer Trash Boom.	The costs of booms depend mostly on type of material used and size. Items manufactured in the US may cost USD 1,214 for a 2.5 metre boom and USD 725 for one that is 1.3 metres. Large booms (typically 30 metres) can cost up to USD 36,000. Overall cost is USD 485-1,200 per metre for a long boom.	Boom placement requires more knowledge of plastic waste flows in NZ to allow for strategic implementation. Booms are unable to remove waste travelling sub-surface. They require operating a separate system to collect the trapped waste (e.g. a clean-up boat). Accumulation of pollutants at the boom can be an eyesore/odorous (socially less accepted).	Support quantification of plastic flows in waterways in NZ. Strategic implementation based on evidence	(Schmaltz et al., 2020)

Leakage source	Technology innovation	Specific examples/advances	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Wastewater runoff (macro-plastics)	Wastewater runoff (before treatment plant)	**Trash racks/meshes** - remove gross pollutants (>5 mm) washed into the stormwater system before the stormwater enters the receiving waters. They generally consist of vertical steel bars (typically spaced 40 – 100 mm apart) and are manually cleaned. Can be retrofitted into existing drainage systems, simple construction. E.g. Adelaide operates a number of trash racks on the Torrens river. Not widely implemented in NZ.	**Investment costs:** Rack structures made of heavyweight rail or steel cost USD 3,000-30,000 or more, depending on the size and materials required. **Operational costs:** manual clean-up - USD 1,800-9,000 mechanical clean-up- USD 2,100-9,700 .	Difficult and expensive maintenance procedures (primarily cleaning operations) can lead to a decline in the trap's maintenance frequency. A poorly maintained trap will reduce its pollutant trapping efficiency and also may potentially become a source of pollutants as collected material break-down. Under-maintained traps can present a flooding risk. Accumulation of pollutants can be odorous and unsightly.	Suitable for targeting problem areas – identification of strategic locations for placement will be required.	https://www.oceannz.co.nz/trash-rack (Fitzgerald & Bird, 2011)
Wastewater runoff (microplastics) PVC, PP, PE, PET, PS	Wastewater runoff	**Retention ponds** Stormwater in treatment ponds in Denmark contained 0.5-22.9 items/litre (about 0.085-1.143 µg/litre; particle size 10-2,000 µm). The lowest microplastics concentrations were measured in ponds collecting stormwater from highways and residential areas. The highest concentrations were associated with industrial and commercial areas.	Retention ponds construction costs vary considerably with hydrogeology.	Cost and land-use are potential barriers for implementation.	Strategic placement of retention ponds near industrial areas to filter microplastics from stormwater runoff.	(Nikiema Josiane, Mateo-Sagasta Javier, Asiedu Zipporah, Dalia Saad Dalia, 2020; Vogelsang et al., 2019)
Wastewater runoff (microplastics)	Wastewater runoff (before treatment plant)	**Gully pots** Sustainable urban drainage systems are used extensively to remove from road run-off water micro-debris. In the city of Oslo, Norway, there are about 30,000 gully pots. Can be manufactured from recycled plastic, >90% capture of particles larger than 0.3 mm, 45% capture for particles smaller than 0.05 mm.	Gully pots require regular maintenance to prevent blockages (council worker costs to empty pots 1-3 times per year).	Blocked gully pots can be responsible for exacerbating flooding.	Incremental implementation, starting with stormwater drains in industrial areas and urban centres.	(Vogelsang et al., 2019)
Wastewater runoff (microplastics)	Wastewater runoff (before treatment plant)	**Infiltration basins** Sedimentation technique which receives stormwater run-off and contains it until the water infiltrates the soils. Accumulated sediments (containing microplastics) must be removed frequently from the basin bottom to avoid clogging of the surface soils, which will make basin cease to operate as designed.	Construction costs vary considerably by hydrology. Maintenance cost ??	Regular maintenance required; it is unclear what should be done with the plastic contaminated sediment that is routinely removed. Mitigates microplastic to ground water/marine environment but traps it in terrestrial environment. Knowledge gap regarding sources of microplastic contamination in ground water needs to be addressed for strategic placement.	NZ already has infiltration basins in Auckland and Christchurch. Singh *et al.* identified 5 potential zones after considering slope, aspect, drainage density, land use, and ground composition with the goal of recharging aquifers (drinking water) – figure to right. Low elevated areas and flat terrains with quaternary sediments have a high potential for groundwater recharge. The added effect of reduced groundwater contamination should be considered. Lower areas for recharge potential should be considered where contamination risk is high (data needed).	(Singh et al., 2019) 
Wastewater treatment in NZ: 45 plants only do primary treatment, 120 stop at secondary treatment, 85 plants have tertiary treatment processes (water NZ WWTP data sheet). Current wastewater treatment plants are not designed with optimisation of microplastics removal during the primary processes in mind. Retrofitting may be very costly. New WWT facilities and upgrades to existing facilities should consider microplastic removal in the design.						
Wastewater treatment plants: Primary treatment (macro-plastics and microplastics)	Primary treatment Removes *ca.* 72% of microplastics	1. Fine screening with metal grids to remove fine debris, i.e. less than 6-10 mm in size 2. Grit removal to remove sand, silt and other heavy particles 3. Skimming tank for grease, oil and fat removal 4. Coagulation and flocculation to create large flocs of heavy metals and phosphorus 5. Primary sedimentation to remove particulate matter and flocs 6. Flotation to remove floating materials and volatile organic compounds and grease.			All NZ water treatment services currently use primary treatment methods that will decrease the microplastic concentration discharged into the ocean. Such plants can be improved by upgrading plants with secondary and tertiary treatment processes that target microplastics.	(Lyare et al., 2020)

<table>
<tr><th>Leakage source</th><th>Technology innovation</th><th>Specific examples/advances</th><th>Estimated costs</th><th>Key barriers to use in NZ</th><th>What would make this successful in NZ?</th><th>References and links</th></tr>
<tr><td>Wastewater treatment plants: secondary treatment (microplastics)</td><td>In combination with primary treatment removes between 88-94% of microplastics</td><td>Biofiltration – bed of microorganisms that oxidatively metabolise many types of organic pollutant. Can remove up to 80% of most types of microplastic that are smaller than 100 µm. More effective for bio-based materials.

Activated sludge - using aeration and a biological floc composed of bacteria and protozoa. Removes carbonaceous pollutants. Similar efficacy to biofiltration. More effective for bio-based materials.

Trickling filters – bed of rocks/coke/gravel/ceramic or plastic media that grow a layer of microbial slime as wastewater flows over it. The microbial communities metabolise pollutants and some pollutants absorb onto the slime. Plastic beds may shed microplastics.</td><td>Biofiltration and trickling filters have lower operational costs than activated sludge.</td><td>Retrofitting plants that currently have secondary and tertiary treatment processes to add tech that targets microplastics is likely too costly to be worth the small increase in effective microplastics removal. Upstream solutions may be better option.</td><td>Future upgrades for plants that only use primary treatment with secondary and tertiary treatment processes that incorporate the processes which target microplastics. Likewise, new plants should be designed with microplastics in mind.
Upstream interventions in regions where waste treatment is already at secondary/tertiary level to minimise flow of microplastics into the WWTP.

These systems are all more effective at microplastic removal when the plastic is bio-based.</td><td>(Klingelhöfer et al., 2020; Schmaltz et al., 2020)</td></tr>
<tr><td>Wastewater treatment plants: tertiary treatment (microplastics)</td><td>Combined with primary and secondary – can remove 97-100% of microplastics</td><td>Membrane bioreactors - the combination of a membrane process like microfiltration or ultrafiltration with a biological wastewater treatment (highest reported microplastics removal efficiency).
Electrodeposition - this technique has been tested in a bench-scale stirred-tank batch reactor (1 L) and could be viable at the large scale using an industrial EC cell with a two-stage, continuous EC reactor/settler unit.
Coagulation/flocculation – uses inorganic coagulants which cause microplastics to stick together. Flocculation is a gentle mixing processes with an organic flocculant that causes smaller coagulated micro-floc particles to aggregate into larger, denser floc that can sink during sedimentation.</td><td>??</td><td>As above. The majority of plastics removed during WWT are retained in sewage sludge that is reused for agriculture. This means that the prevention of leakage to the marine environment is somewhat transferred to terrestrial environment – more research is needed regarding the environmental fate and impact of microplastics in sludge-amended soils.

Electrodeposition is promising but has not been proven at scale.</td><td>As above</td><td>(Hou et al., 2021)</td></tr>
<tr><td>Water treatment downstream of discharge</td><td></td><td>Wetlands
Reduce plastics and microplastics in run-off or secondary treated wastewater. Treatment wetlands (both natural and constructed wetlands) can be considered an end-of-pipe solution to reduce the volume of microplastics entering streams, rivers and oceans, while floating wetlands provide an ongoing treatment process for freshwater systems. Microbes and plants biodegrade materials in the wetlands, design for plastic.
Examples
Wetlands appear able to remove high levels of microplastics, as reported by one study.<table><tr><th>Facility</th><th>Örsundsbro wetland, Sweden</th><th>Alhagen wetland, Sweden</th></tr><tr><td>Area (ha)</td><td>0.8</td><td>28</td></tr><tr><td>Mean flow (m^3/day)</td><td>667</td><td>5,100</td></tr><tr><td>Theoretical residence time (day)</td><td>3.5</td><td>86</td></tr><tr><td>Reduction efficiency: microplastics 20-30 µm (per cent)</td><td>99.7</td><td>99.8</td></tr><tr><td>Reduction efficiency: microplastics > 300 µm (per cent)</td><td>100</td><td>100</td></tr></table>UK has 39 constructed wetlands.</td><td>Wetlands are generally classified as low-cost technologies.
Investment costs: Costs can vary greatly, depending upon initial site conditions but consider costs of earthworks and planting.
Operational costs: Typically, USD 0.35-0.99 per m2/year This is equivalent to up to USD 40- 400 per m3/day treated for the entire system.</td><td>The opportunity cost of any land removed from agricultural production is not negligible. The long-term effectiveness is not well known. Effects of wetland aging may jeopardize treatment performance. Temperature and flow fluctuations can cause a wetland to display inconsistent contaminant removal rates.
Sediment in wetlands may have higher microplastics concentrations than water being treated.</td><td>Wetlands fit with NZ green image.
Hotspots for plastic leakage would need to be identified.

Would work best in a bio-based plastics economy – microplastics accumulated in wetlands can biodegrade.</td><td>(Nikiema Josiane, Mateo-Sagasta Javier, Asiedu Zipporah, Dalia Saad Dalia, 2020)(Ellis et al., 2003)</td></tr>
</table>

Recycling technologies

- Implementation of new recycling technologies will invariably involve a substantial capital investment for construction of infrastructure required. This can include requirements for collection infrastructure, sorting infrastructure, recycling plant facility construction etc.
- Recycling technologies present opportunity for valorisation of waste and cost-savings in landfill/incineration.
- Successful recycling schemes will rely on recycling labels and consumer awareness/compliance. Recycling schemes include sorting, primary and secondary recycling, tertiary recycling, and waste to energy.

Sorting technologies

Modern materials recovery facilities use combinations of sorting technologies integrated across the processing line [see case studies in (Neidel & Jakobsen, 2013)]. Retrofitting new tech into MRF sorting lines may not be feasible. New MRF facilities should consider all new sorting technologies when designing the facility.

Table 3: technologies and innovations in sorting of plastic waste

Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Fluorescent labelling	Nextek's PRISM – fluorescent/luminescent labelling of plastics for easier sorting out of food grade plastic using UV light. Following commercial trials PRISM is ready for the market.	Product manufacturer cost for labelling materials. Fluorescent readers relatively cheap.	Industry compliance? Calibration of optical sorters in operation.	Compatible with current NIR optical sorters. Working packaging sector to make this standard practice.	https://www.nextek.org/project/prism-innovate-uk/?cn-reloaded=1
AI and robotic assisted sorting	Veolia's SALTO system. Uses algorithm to control a single machine for sorting 5 types of plastic. Lalugue, France implemented in facility that sorts approx. 23 000 MT per year with 15% improvement in operational productivity compared to the previous sorting line.	Capital costs high Operation cost ??	Recent investment in optical sorters unlikely to invest here in near future?		https://www.veolia.com/en/csr-natural-resources/innovative-waste-sorting-better-materials-recycling
IR/Laser assisted sorting	Germany-based INEOS Styrosolutions, with equipment firm Tomra, used near infrared sensor technology, to separate polystyrene in 99.9% purity from consumer plastic waste streams. Eagle Vision, which is able to pre-sort PET, PE, PP, PS, PVC, and PLA using NIR analysis to help remove undesirable plastics from other main streams. Titech and Unisensor are commercial examples of NIR systems that are able to discriminate between PET and PLA with accuracies higher than 97%, which is an acceptable amount for maintaining good properties for reprocessed PET. Automatic sorting of other biopolymers, like PHB and starch, or blends is also possible by NIR.	Capital cost high Operational costs??	Recent investment in optical sorters), unlikely to invest here in near future? NIR cannot identify black or dark products.		http://eaglevizion.com/ https://koasltd.com/ckfinder/userfiles/images/PDF/Titech/Makineler/Autosort_eng.pdf
Density difference and hydrocyclones	Tanks with water or aqueous salt solutions or alcohols used to separate different polymers that float and sink in the medium (polymer density dependent).	Probably the most cost-effective method, but limited in ability to separate similar density polymers. Multi-stage process needed to separate all plastics in the waste stream (minimum 6 tanks).	Infrastructure required		(Gent et al., 2009)

Table 1: Summary of published results of industrial or pilot plant density separation processes for plastics recycling.

Plastics treated	Reference	Separation process	Products	Product purity (%)	Recovery	Particle sizes and forms
ABS–HIPS	Rosenzweig (2004); Kobler (2008, pers comm)	RPI–static media	ABS HIPS	~ 90 90	90 80	< 9.5 mm
Rubber–PP–PE–ABS–ABS/PC–PC–PS–PVC	Jody & Daniels (2006)	Argonne-Static media and froth flotation	PE-PP ABS ABS–PS PC–ABS/PC	> 95 70 60 85	NI NI NI NI	6.4–9.5 mm
PE– EP– UP– POM– PC–HIPS– ABS	Schlummer *et al.* (2006)	Static media and dissolution	HIPS–ABS	~ 100	~ 90	~ 10 mm
PS–ABS–PET	Tsunekawa *et al.* (2005)	Jigging	PET ABS PS	99.9 98.7 96.7	NI	< 7 mm

Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Magnetic density separation (PP, HDPE, PS, PET, ABS and PVC)	Magnetic mixture (FeO nanoparticles suspended in water) where density varies vertically in a magnetic field. Enables sorting of polymers with similar density. Umincorp industrial scale plant (Amsterdam) can process 1.5 t/hr and separates polymer groups into streams with 99% purity.	Umincorp claims that their total chain of plastics can be up to 75% more cost effective than current methods of recycling.	Infrastructure required		http://www.umincorp.com/solutions
Triboelectric separation (PET, PP, PP, ABS and PVC)	Friction is used to load the surfaces of the polymers that are separated according to their anionic or cationic character.	Unknown, infrastructure costs probably high.	Infrastructure required		http://www.prodecolog.com.ua/production/electric_separators/tribo_electric/ebs_t/
Plastic markings/QR codes to assist sorting and separation	Markings should contain information on all aspects of the material, including additives and other information relevant for reprocessing the material. Curby bag for soft plastics in kerbside collection (Australian pilot).	Product manufacturer cost for labelling materials. Council cost for initiative like curby bags.	NZ MRFs may need to be retrofitted for automated sorting	Incremental implementation by phasing out import of plastic products that do not contain adequate labelling. Use of household bags labelled with QR codes for consumer sorting before kerbside collection Working with packaging sector to make this standard practice.	https://www.curbythebilby.com.au/#:~:text=Register%20for%20Trial-,What%20is%20Curby%3F,tightly%20and%20attach%20a%20CurbyTag
Mobile apps for better consumer sorting of waste	Recyclemate (Australia) photo-recognition ap that directs consumer to where it can be recycled, including container deposit locations and return to store options. Pilot being released in June 2021.	Unknown	Development of NZ version required.	Development of NZ app similar to Recyclemate that contains the local recycling information for NZ regions.	http://www.acor.org.au/recycle-mate.html

Primary and Secondary Recycling

Primary recycling creates plastic of same quality (e.g. mechanical recycling of PET bottles) while secondary recycling creates downgraded plastic material. Primary closed-loop recycling is most desirable in alignment with circular economy principles but is not technologically feasible for most materials.

Table 4: Technologies and innovations in primary and secondary recycling

Level of recycling and type of plastic	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Primary closed loop	Soft plastic recycling back to food grade soft packaging (pilot program in Australia) that uses The Cat-HTR™ chemical recycling system (hydrothermal upgrading). https://softplastics.5stream.com/#/play/66915/ *	Nestle-IQ renew trial – yielded a prototype plant for soft plastics recycling from kerbside waste (Curby soft plastic recovery solution) Curby tag = QR code sticker to allow for sorting from kerbside collected recycling stream. With over $75M invested over 10 years of development, the Cat-HTR™ is the only platform of its kind proven at large pilot scale and now commercial ready. In 2017 Licella formed Cat-HTR plastics, (“CHP”), as a wholly owned subsidiary and gave it the global rights to utilize the Cat-HTR™ platform for a defined plastic feedstock excluding Australia and New Zealand.	High infrastructure cost for chemical recycling capability **Investment cost** of Licella’s Cat-HTR plant, was estimated to be $40–50M (AUS). The processing capacity of this plant is approximately 20,000 tonnes per year, and creates around 18 jobs **Operation costs:** $2.25M/kt	Requires infrastructure for onshore chemical recycling of soft plastic (and refining of oil to resin?). Scale up needs to be proven.	Potential to export curby bags of soft-plastic to Australia? Investment in the chemical recycling infrastructure for onshore closed loop system Licella is operating at commercial scale, NZ excluded from global patent. Revenue and cost savings are possible once operating at scale	https://www.curbythebilby.com.au/#:~:text=Register%20for%20Trial-,What%20is%20Curby%3F,tightly%20and%20attach%20a%20CurbyTag https://www.iqrenew.com/technology/
Primary and secondary	Advances in polypropylene recycling (3rd highest use resin)	PureCycleTechnology: first industrial plant (Ohio, USA) began operating 2021. Will have capacity to process 119 million pounds of PP per year, producing *ca.* 105 million pounds of virgin-like resin per year. They have begun site selection for a second plant in Europe.	Unknown. Capital investment likely to have high cost.	Infrastructure required. Adequate sorting at MRFs required.	Investment in chemical recycling plants. Investigate cost-effectiveness of smaller scale operation if NZ PP in waste stream is low.	https://purecycletech.com/
Secondary	Compatibilisers-enable recycling of mixed-material plastic wastes into new plastic products.	HDPE and PP compatibiliser (olefin block copolymer). PET and PLA compatibiliser.	??	Infrastructure required	PET-PLA compatibilisers would be advantageous if NZ were to incrementally introduce bio-based plastics during a petrochemical-based plastic phase-out. Compatibilisers represent an opportunity to increase the value of mechanical recycling of mixed polymer waste streams (improved properties of recyclate).	(Karaagac et al., 2021) (HDEP-PP) (Gere & Czigany, 2020) (PET-PLA)
Secondary	LDPE and HDPE de-inking	APK AG’s solvent-based recycling technology Newcycling can fully remove inks from the polymer matrix (LDPE and HDPE). Cadel Deinking – reusable water based formulations used to remove ink from LDPE,HDPE, PP, and PET -pilot plant in Spain with treatment capacity of 100kg/hr.	Capital cost for deinking and recycling to virgin like pellet approx. $1 million with predicted return on investment approx. 16%. Operational costs ??	Unclear what happens to the ink waste.	Incorporation of film de-inking processes at new chemical recycling plant(s) if they are invested in.	https://www.apk-ag.de/en/siegwerk-and-apk-ag-succeed-at-de-inking-of-plastic-film-recyclate/ https://www.apk-ag.de/en/ https://www.ou.edu/class/che-design/a-design/projects-2005/De-inking%20Presentation.pdf http://cadeldeinking.com/en/#_process

* CAT-HTR alone fits under tertiary recycling. Here we are describing the whole closed loop primary recycling scheme trialled in Australia.

Level of recycling and type of plastic	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Secondary	Mobile recycling of plastic bottles into tiles that can be used as decoration or in construction (flooring and insulation).	Miniwiz Trashpresso mobile autonomous tool comprising a 40 foot container housing a mechanical processing line (shredder, washer, dryer) and hot moulding facilities to create tiles, powered by separate mobile solar panel unit (20 foot). Can upcycle 50 kg of plastic waste per hour. Recycling process uses 100L of water with no water loss in the process (looped back through three steps of filtration).	?? lower than industrial scale recycling plants	Currently only produces tiles, trashpresso 3 aims to implement more moulding options for a more versatile end product range	Could be a viable alternative for increased recycling in rural communities?	https://trashpresso.com/
Secondary	Wood-Plastic composites (WPCs). Can incorporate PE, PP, PVC, PS or PLA to instil different properties in the material. Moisture and rot resistant, can be used in construction projects in the same way as natural lumber but last longer, more heat resistant and less likely to split or warp.	Production of new material by combining plastic waste and woody biomass (typically sourced from forestry waste) most commonly made with recycled HDPE. Biform (NZ company) manufactures WPC decking material from waste streams. Scion (NZ company) manufactures wood fibre dice that can be used to make any product by injection moulding. It is unclear if they use virgin resin or recycled resin?	WPCs process at lower temperatures compared to plastic-only material (cheaper/less energy intensive manufacture of end products by injection moulding).	Transportation of plastic and forestry wastes to one location for recycling may be a cost barrier. The inclusion of plastic results in potential for higher fire hazards compared to wood.	Recycling of two waste streams supporting circular economy aims. Forestry waste is widely available in NZ. Onshore infrastructure for WPC construction already exists. Scion and Biform industry leaders in this area in NZ. Could be a good way to recycle HDPE and LDPE in NZ	https://biform.co.nz/ https://www.scionresearch.com/science/bioproducts-for-sustainable-industries/woodforce

Tertiary recycling

Creates plastic monomers/oil that can be used for feedstocks to create new plastic.

Recovers more waste types than mechanical recycling because it recycles the plastic waste usually sent to landfill or incinerated. Mixtures of plastic materials can also be processed for some technologies. The process saves typically 1.5 metric tons of carbon dioxide per metric ton of plastic (compared with 2.3 metric tons in the case of mechanical recycling).

Table 6: Technologies and innovations in tertiary recycling

Level of recycling and type of plastic	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Secondary and tertiary PET, PA, PU and PLA	Solvolysis: Solvent depolymerises the plastic by cleaving the polymer chains. Can be totally depolymerised or partially. Usable as a pre-treatment method to enable further recycling.	Glycolysis of PET is the most advanced in terms of demonstrating commercial viability on a larger scale (Nan Ya Plastic's ECOGREEN, Ioniqa technologies and Jeplan) There are far fewer reported technologies approaching commercial scale operation for PU, PA or PLA. A notable exception is Nylon (Econyl by Aquafil) which operates industrially.	?? capital investment costs are likely to be high Operational costs??	Catalyst recovery can be problematic, catalyst details are not disclosed. Limited to certain types of plastic. There is a consistent lack of information regarding demonstrated process yields at larger scale plant level.		https://ioniqa.com/applications/ https://www.aquafil.com/sustainability/econyl/ (Hann & Connock, 2020)
Polyolefins (PE LD and HD) PVC Textile waste	Solvolysis in super critical fluids	BASIL process by BASF to scavenge acids in the synthesis of alkoxyphenylphosphines was commercialized in 2002 and has shown to be much more environmentally friendly than the previous process using tertiary amines. Trash-2-Cash focuses on cellulose regeneration by using an ionic liquid in which the cotton is dissolved and can be separated from the polyester. They focus on using their patented ionic liquid, Ioncell F, to selectively dissolve the cellulose portion in mixed textiles.	?? ionic liquids suffer from high toxicity, poor biodegradability and often high costs. But can be recycled.	Still at lab scale phase	Demonstration of commercial scale operations	(Vollmer et al., 2020) https://www.trash2cashproject.eu/trash-2-cash-about-page
PS extrusion, PP/PA or PP/PET multilayer films	Dissolution/precipitation Plastics that are soluble in specific types of solvent are dissolved. Can involve a number of solvents used in staged manner to ensure effective removal of impurities	CreaSolv process – Fraunhofer and CreaCycle NewCycling process – APK AG	Capital cost high? Operation costs ??	At lab scale, there are demonstrated examples of environmentally benign solvents that can dissolve specific polymers, at plant level there is little detail as to precisely which solvents are utilised, nor the quantities required, making general claims regarding toxicity/hazardous waste difficult to verify.	Demonstration of industrial scale plant using environmentally friendly solvents.	https://www.creacycle.de/en/the-process.html

<table>
<tr><th>Level of recycling and type of plastic</th><th>Technology/innovation</th><th>Specific examples/advances and commercial operation examples</th><th>Estimated costs</th><th>Key barriers to use in NZ</th><th>What would make this successful in NZ?</th><th>References and links</th></tr>
<tr><td>Secondary and tertiary</td><td>Polystyrene chemical recycling by pyrolysis</td><td>Ineos styrosolution in partnership with Agilyx – multiple commercial scale plants in operation. European patent issued 2021.

Agilyx reduces transportation costs by dissolving waste polystyrene in cymene-containing concentrators set up at customer locations. It then brings the polystyrene-rich solvent to a central location where it filters out contaminants and recrystallizes the polymer.</td><td>Unavailable?
Capital cost high.
Operational cost presumably high.
Tech is patented.</td><td>Phase out of expanded polystyrene products means that NZ may not have a sufficient waste stream to implement this tech.</td><td>Infrastructure for chemical recycling and sorting of PS in kerbside collection required for successful implementation</td><td>https://www.agilyx.com/our-solutions/innovations

https://www.ineos-styrolution.com/portal/about-us</td></tr>
<tr><td>Tertiary; polyesters (PET, PLA, PA)</td><td>Enzyme depolymerisation of plastics (bio-recycling)</td><td>CABIOS – first pilot plant built in 2016, industrial plant expected to be operational in 2023

Lab scale: LCC protein engineering have yielded enzyme that can catalyse the depolymerisation of PET waste at 72 C to 90% conversion in less than 10 hours (16.7g/lh using 0.3 wt% enzyme. Cost was estimated to be ca. 4% of the cost of virgin PET.</td><td>??

Cost was estimated to be ca. 4% of the cost of virgin PET.</td><td>Not tested at industrial scale</td><td>Aligns with circular bioeconomy principles. Implementation if plastics economy moves towards PLA</td><td>https://carbios.fr/en/technology/biorecycling/
(Sheldon & Norton, 2020)</td></tr>
<tr><td>Tertiary + quaternary; suitable for mixed plastic materials. Does not deal well with organic contamination.</td><td>Pyrolysis (conventional thermal cracking)</td><td>Already in commercial operation

Industrial facilities for plastic pyrolysis. Source: Adapte
Plastic Energy (2019), Ragaert et al. (2017) and Samperi
<table>
<tr><th>Process</th><th>Temperature, °C</th><th>Feedstock, %</th></tr>
<tr><td>PYROPLEQ</td><td>450–500</td><td>PW, MSW</td></tr>
<tr><td>Akzo Nobel</td><td>700–900</td><td>PVC rich PW</td></tr>
<tr><td>PKA-Kiener</td><td>450–500</td><td>PW, MSW</td></tr>
<tr><td>Siemens - KWU</td><td>450–500</td><td>PE, PP, PS</td></tr>
<tr><td>DBA process</td><td>450–500</td><td>PW</td></tr>
<tr><td>Kobe Steel</td><td>450–500</td><td>PW</td></tr>
<tr><td>Ebara</td><td>Unknown</td><td>PW</td></tr>
<tr><td>Mogami-Kiko</td><td>Unknown</td><td>PP (67), PE (33</td></tr>
<tr><td>Hitacho-Zosen</td><td>Unknown</td><td>PE (55), PP (28
PS (17)</td></tr>
<tr><td>Royco Beijing</td><td>Unknown</td><td>PE, PP, PS, waste oils</td></tr>
<tr><td>Chiyoda process</td><td>Unknown</td><td>PW</td></tr>
<tr><td>Plastic Energy</td><td>Unknown</td><td>Plastic waste</td></tr>
</table>

Regenyx (Agilyx’s PolyUsable technology) – commercial plant ca. 3000 t/year PS waste</td><td>Investment costs: USD 260 million plant in Ashley, Indiana for a plant with: - Capacity: 91,000 tons per year of plastic waste Output per year: 68 million litres of diesel and naphtha, and 22 million litres of industrial wax
Operation costs: For a pyrolysis plant with capacity of:
15,000 metric tons per year - USD 800 per metric ton in North America and USD 1,000 per metric ton in Europe
55,000 metric tons per year - USD 500 per metric ton in North America and USD 600 per metric ton in Europe

Process efficiency and profitability vary depending on feedstock mix and quality.</td><td>High investment costs. Has so far failed to achieve commercial viability long-term on an industrial scale due to the trade-offs between energy inputs and quality of output.

This type of recycling will not be attractive when oil prices are low.
It is only profitable when large volumes can be processed (50,000-100,000 MT/year).

Profitability is reduced and net present value (NPV) remains negative even after 15 years of operation.</td><td>Innovation to develop cost-effective smaller scale approaches. Pyrolysis can be implemented cost-effectively on a smaller scale compared to gasification.</td><td>(Nikiema Josiane, Mateo-Sagasta Javier, Asiedu Zipporah, Dalia Saad Dalia, 2020; Solis & Silveira, 2020)</td></tr>
</table>

<table>
<tr><th>Level of recycling and type of plastic</th><th>Technology/innovation</th><th>Specific examples/advances and commercial operation examples</th><th>Estimated costs</th><th>Key barriers to use in NZ</th><th>What would make this successful in NZ?</th><th>References and links</th></tr>
<tr><td>Tertiary + quaternary, only well studied for pure polymers, mixed plastic streams may be problematic</td><td>Catalytic pyrolysis: With a catalyst added, the process temperature can by reduced by 150°C and higher value monomer yields can be increased.</td><td>Already in commercial operation overseas
Industrial facilities for plastic catalytic cracking.Klean Source: A et al. (2011), Fukushima et al. (2009), Industries (2015), Ragae Samperio (2016).
<table>
<tr><th>Process</th><th>Temperature, °C</th><th>Catalyst</th><th>Feedstock</th></tr>
<tr><td>Zadgaonkar</td><td>350</td><td>Unknown</td><td>PE, PP, PS, PVC PET</td></tr>
<tr><td>Smuda</td><td>350</td><td>Ni-silicate, Fe-silicate</td><td>PE, PP, PS, PVC PET</td></tr>
<tr><td>T-technology</td><td>390–420</td><td>Unknown</td><td>PE, PP, PS</td></tr>
<tr><td>Fuji</td><td>390</td><td>HZSM5</td><td>PE, PP, PS</td></tr>
<tr><td>Amoco</td><td>490–580</td><td>Unknown</td><td>PE, PP, PS</td></tr>
<tr><td>Mazda</td><td>200–450</td><td>Al_2O_3, $ZrCl_4$</td><td>ASR, PE, PP, PS, PU, ABS</td></tr>
<tr><td>Nikko</td><td>200–250</td><td>Metal catalyst</td><td>PW</td></tr>
<tr><td>Reentech</td><td>350–400</td><td>Al-silicate</td><td>PE, PP, PS, PVC</td></tr>
<tr><td>NanoFuel</td><td>270–370</td><td>HY</td><td>PP, PE, biomas</td></tr>
<tr><td>Thermofuel/ Cynar</td><td>350–425</td><td>Metal catalyst</td><td>PE, PP, PS</td></tr>
<tr><td>Fuji process</td><td>400</td><td>HZSM5</td><td>PE, PP, PS, PET, PC</td></tr>
</table>
GreenMantra Technologies – commercial plant (5000 t/year) PE, PP and PS waste

ReNew IQ Cat-HTR – commercial plant in Australia (20000 t/year) – uses water so is very green option</td><td>Capital costs likely to be high
Operational costs ??</td><td>Chloride, nitrogen and inorganic materials components present in the raw waste stream tend to deactivate the catalyst. Pre-treatment of the waste is often required.

The gases produced from pyrolysis of some plastic waste such as PVC are toxic, and therefore pyrolysis emission treatment technology has to be further refined to achieve maximum environmental benefits.</td><td>NZ is excluded from ReNew IQ Cat-HTR patent. This could be the cheapest option for implementation in NZ.

Collaboration and consultation with Australia/Licella.

The market for pyrolysis based biorefinery products should be created/ expanded to attract further interest and funding, in order to make this concept more practical and successful.</td><td>https://www.iqrenew.com/technology/
(Miandad et al., 2019; Solis & Silveira, 2020)</td></tr>
<tr><td>Tertiary</td><td>Microwave-assisted pyrolysis
Microwave irradiation elevates the surface temperature of the molecules, allowing for lower temperature reactors.</td><td>Lab and pilot scale only
Pyrowave employs industrial microwave reactors to depolymerize PS to form monomers. Can also be used to process PP and PE</td><td>?? capital costs high
Operating costs likely to be reasonably high</td><td>Not ready for industrial scale up – lab scale demonstrations only (200 kg/day). Pyrowave has commercial scale operation (200 kg/hr)</td><td>Evidence of successful scale up required before implementation</td><td>(Arshad et al., n.d.; Ding et al., 2019; Ludlow-Palafox & Chase, 2001)
https://www.pyrowave.com/en/pyrowave-technology</td></tr>
<tr><td>Tertiary</td><td>Chemical recycling with non-metal catalysts</td><td>Organocatalysts can be an alternative to the biocatalysts for depolymerisation processes (perhaps more stable, better TON and longer life cycle, easier to mass produce etc). Examples: tetramethyl ammonium methyl carbonate catalysed the transesterification of various polyesters – PLA, PET, PCL and PC to provide monomeric esters suitable for virgin plastic production. BUT requires organic solvents.

BioCellection, Inc. has successfully recycled HDPE and LDPE through a patented process referred to as accelerated thermal oxidative decomposition (ATOD). oxidizing acid, such as HNO_3, to treat mixed PE waste at 60‑200° C for 30 min‑30 hr. The resulting mixture is purified to yield the various organic acid compounds.</td><td>Capital costs likely to be high

Operation costs - unknown</td><td>Lab-scale demonstrations only</td><td>Evidence of successful scale up required before implementation</td><td>https://www.novoloop.com/technology
(Hatano et al., 2018)</td></tr>
</table>

Level of recycling and type of plastic	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Tertiary PS, HDPE and LDPE	Photodegradation (UV light)	Photocatalytic oxidation reactions can occur under moderate conditions, such as room temperature, one atmosphere pressure, and molecular oxygen as the only oxidant and TiO2 catalyst.	Costly	Lab and pilot scale only	Environmentally friendly compared to other chemical recycling techniques.	(Craig & White, 2005; Shahnawaz et al., 2019; Shang et al., 2003)
Tertiary	Delamination of multilayer materials	Separation of the layers expands the options available for recycling, and widens the scope of blending strategies. Enval – industrial scale delamination plant for separation of plastic-aluminium laminates (microwave assisted pyrolysis) Innoget and Vintex – lab scale mechanical method for removing adhesive between the layers of multilayer plastic films that is followed by de-inking. Seeking collaboration for commercial scale up.	Enval claims that an industrial scale plant with 2000 t/year capacity will pay for itself in 4 years and will provide maintenance and engineering support for the lifetime of the plant. Costs and profits not disclosed.	New sorting innovations needed for segregation of multi-material films required to recycle from kerbside waste. Infrastructure investment costs.	Collection scheme for films used in shipping?	https://www.enval.com/plant/ https://www.innoget.com/technology-offers/7866/multilayer-film-delamination-process-for-plastics-recycling#:~:text=Summary%20of%20the%20technology&text=As%20the%20reactant%20accesses%20the,of%20this%20technology%20are%20sough. http://sangiaodichcongnghe.vn/Process-for-the-Delamination-of-Multilayer-Plastic-Film.html

Waste to energy technologies

Classified as quaternary recycling – recycled out of the plastics system. This is a last resort option for waste that cannot be recycled or reused and presents a valorisation of waste that would otherwise be landfilled or incinerated without energy capture. This is oppositional to circular economy principles but realistically there will always be flow of plastics into some end-of-life process. Converting plastics at end of life into energy is preferable to environmental leakage.

Table 5: Waste-to-energy technologies

<table>
<tr><th>Level of recycling and type of plastic</th><th>Technology/innovation</th><th>Specific examples/advances and commercial operation examples</th><th>Estimated costs</th><th>Key barriers to use in NZ</th><th>What would make this successful in NZ?</th><th>References and links</th></tr>
<tr><td>Quaternary mixed plastic waste streams</td><td>Conventional gasification
Impurities can be removed from the gaseous end product using gas purification, and therefore contaminated plastic waste can also be used to produce a clean raw material.</td><td>Already in commercial operation
Industrial facilities for plastic gasification process. Source: Adapted from Nistelrooij (2017) and Samperio (2016).<table><tr><th>Process</th><th>Temperature, °C</th><th>Feedstock, %</th><th>Yield</th></tr><tr><td>Ebara, TwinRec</td><td>500–600</td><td>PW, ARS</td><td>energy and metals</td></tr><tr><td>Texaco</td><td>1200–1500</td><td>PW (10)</td><td>gas</td></tr><tr><td>Lurgi (SVZ)</td><td>1600–1800</td><td>PW, ARS, waste oil, lignite, WEEE</td><td>gas, CH_3OH, energy</td></tr><tr><td>Enerkem</td><td>unknown</td><td>household waste</td><td>oil, alternative fuels</td></tr></table></td><td>Capital costs of gasification plant are similar to incinerator plant but investment for gasification is lower because of reduced amount of flue gasses (less post-processing required).

Operating expense: most significant cost is electricity; however, the plants can be designed to self-power.</td><td>High investment costs, high energy consumption.

Ash fouling can lead to economic problems because of reduced efficiency in gasification.

Some hazardous emissions.</td><td>The target of zero-approaching plastic waste and real circular economy can be reached in a medium term by enlarging the industrial system of plastic-to-oil and plastic-to- chemicals processes, by substituting the large-scale combustion plants with smaller-scale integrated gasification plants and by using the electricity produced by these plants to lower the opex of treatment facilities. The evaluation of operating expenses for these systems has shown that the electricity represents the main cost; its production should be incentivized for self-use instead of putting energy into the grid.</td><td>(Mastellone, 2020)</td></tr>
<tr><td>Quaternary</td><td>Plasma assisted gasification

Solves the problem of toxic compounds in syngas as the temperature is high enough to decompose them and limit the formation of free chlorine from HCl. investigated only at laboratory scale</td><td>100 kg/h pilot plant MNIS owned by Bell Production SpAa
- Does not produce harmful emissions, Slag waste product can be reused in construction
- Standard plant design provides waste disposal for community of ca. 10 000 (25 tons/day)
- Modular plant allows for equal efficiency when waste stream ranges from 30-100% capacity</td><td>Investment costs: USD 106 million plant in California -with capacity: 99,000 tons/year of plastic waste
Operational costs: USD 108/ton or USD 260,000-550,000 to process 1 ton/day capacity</td><td>high investment costs, high energy consumption.

Investing in an improved waste- incineration process that prevents the forming of dioxins makes developing a more environmentally friendly alternative to PVC later on less attractive.</td><td></td><td>www.mnis.it</td></tr>
<tr><td>Municipal solid waste and industrial waste streams. PVC, and polyurethane not suitable.</td><td>Refuse-derived fuel</td><td>UK is a large exporter of RDF – ca. 2.5 MT/year. Italy, Denmark, Belgium and Netherlands have established Kilns for RDF production.
Enerkem (Canada) uses mixed MSW to produce syngas, ethanol and methanol using gasification techniques.
Sierra energy convers mixed MSW to Syngas, hydrogen, diesel and ammonia (high value end products).</td><td>Capital cost – high
Operational costs??
Valorisation of mixed MSW</td><td>High investment costs, high energy consumption.</td><td>Potential way to deal with waste streams that are unsuitable for other recycling plants.</td><td>(Kumar et al., 2020)
https://enerkem.com/process-technology/technology-comparison/
https://sierraenergy.com/technology/fastox-gasification/</td></tr>
</table>

Alternative materials – Bio-based and Biodegradable:

Creation of onshore manufacturing facilities and recycling facilities for this material will invariably involve high capital costs. Areas where there are already onshore manufacturing of such materials will require investment for scale up.

- Small and medium enterprises (SMEs), such as Scion (NZ), Aduro biopolymers (NZ, meat works industry specific), Novamont, Biotec, Rodemburg Biopolymers, Cereplast, Tianan, as well as large chemical companies, such as Braskem and Dow, are very active in the field of bio-based plastics. Despite the existence of numerous plastic materials with a high bio-renewability, only a small fraction of these have found a place in commercial applications. The heaviest challenges will be to reduce the high cost of production and processing, minimize agricultural land use and forests, avoid competition with food production.
- Novamont SpA = major starch bioplastics producer (Mater-Bi) www.novamont.com
- Amynova Polymers GmbH produced starch-based 'CropCover', adhesive applied with pesticides and foliar fertilisers to reduce their rinsing during heavy rainfall www.amynova.com
- Biologische Naturverpackungen GmbH & Co. KG www.biotec.de and Cardia Bioplastics www.cardiabioplastics.com both produce and sell a new generation of customized thermoplastic materials
- NaturePlast produces bio-composites that exploit waste as feedstock + hemp as natural plant fibre filler www.natureplast.eu

Some broadly applicable barriers:

- Debate is ongoing about assessing the extent to which biodegradability and (home) compostability of plastic is beneficial in the context of the transition towards a circular economy – recycling and valorisation of waste are better options. Some biodegradables can (and should) be recycled.
- To date, not many companies have commercialised bioplastics on an industrial scale, there are some advanced stage commercial scale plants starting in China and India, but these are still far from producing the megatons that are needed for having an impact on the sector.
- Companies developing new plastics need to invest significant resources ($ and time) in self-assessing product biodegradability and sustainability and in certification.
- Bio-based plastics are more expensive to produce than petro-based ones, especially when crude oil price is low.
- Requires standards of labelling i.e. biodegradable in water, ocean biodegradable, home compost, industrial compost, okay to go into recycling stream etc. The variety of labels has the potential to cause confusion.
- Biodegradability is not always desirable because it can also encourage single-use and littering behaviour.
- Plant-based biodegradable plastics are often rated with a zero or negative carbon footprint. However, when carbon emissions are calculated in life cycle assessments (LCAs), the losses (e. g., land use, by-products) and the carbon emissions during manufacturing are often disregarded.
- There is potential for bioplastics to contaminate the existing mechanical recycling streams, requirement for good sorting potential if implementation in NZ is desired.
- With the growing demand, the expansion of cultivable land area is required as the feed stock of the biopolymers will increase. This may have a negative impact on the production of food, feed, and pasture.
- Little is known about the technical qualities of secondary bioplastics after one or more recycling cycles.

this list is by no means comprehensive. Have not considered blends/composites and the myriad of materials in the research/lab scale phase.

Table 2: Alternative materials for replacing plastic

Material classification	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Biodegradable	Polycaprolactone diol, polybutylene adipate terephthalate (PBAT), and polyvinyl alcohol (PVA) produced by microbes	Several companies produce PBAT on industrial scale with materials used in packaging, mulch film and cutlery: BASF (Germany) Ecoflex 60 000 t/year KINGFA (China) Origo-Bi 40 000 t/year NOVAMONT (Italy) ECOPOND 150 000t/year	Capital costs: high for onshore manufacturing and industrial compositing	Requires suitable conditions and microorganisms that are not always reliable in environmental conditions. Requires industrial compositing facilities.	Innovation in PBAT and PVC recycling – biodegradation for leaked plastic only	https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecoflex.html https://www.novamont.com/eng/read-press-release/novamont-increases-mater-bi-production-to-150000-tonnes/ (Jian et al., 2020)
Bio-based drop-in	100% bio-based alternative to PET, PA and PE New material: polyethylene furandicarboxylate (PEF) analogous to PET	Avantium developed PEF, that is derived from ethylene glycol and furan-2,5-dicarboxylic acid. PEF has superior mechanical, thermal and gas barrier properties compared to PET and LCA showed a GHG reduction of 55% compared to petrochemically derived PET. commercial scale plant in operation. Industrial plant construction began in 2019 – expected to be operational at 300-500Kt/year capacity in 2024. PEF can be separated from PET by IR sorting and recycled to 'rPEF' using the same steps as PET (mechanical or chemical recycling using same steps as PET).	Capital costs: high for onshore manufacturing	Renewable bio-feedstocks cannot displace food supply – sustainable feedstock production must be established for these to become better alternatives.	Could potentially allow for switch away from PET and still make use of existing PET sorting and mechanical recycling infrastructure. Policy support needed for widespread adoption.	https://www.avantium.com/technologies/yxy/ https://www.bioplasticsmagazine.com/en/news/meldungen/20180815ETH-research-team-develops-energy-efficient-and-fast-PEF-production-method.php (Reichert et al., 2020)

Material classification	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Biobased and biodegradable	PLA made from corn and corn by-products. Fermentation and then polycondensation.	NatureWorks LLC (Minnetonka, MN, USA) developed a continuous process to produce PLA from corn-derived dextrose on an industrial scale Ingeo® largest scale manufacturer globally (150 Kt/year) Large amounts of research are ongoing about the copolymerization of lactide molecules to improve the biodegradation of PLA.	Corbion Purac plant in Thailand produces 75 ktpa with a CapEx of approx €60 M, compared to €200 M for the Total Corbion 100 ktpa PLA plant in France.	Requires light and oxygen for degradation processes – not going to break down in most environments so industrial composting facility required. Difficult to separate from PET, potential to contaminate the PET mechanical recycling streams.	PLA is the dominant biobased biodegradable plastic. Industrial manufacture is proven. Onshore manufacturing (Scion) at pilot scale – support for scale up. Investment in scale up of onshore manufacturing + adequate sorting at MRF (see Eagle vision above) and industrial compositing facilities. PLA is a good candidate for environmentally sound chemical and mechanical recycling. Policy and manufacturing infrastructure support to facilitate wide scale adoption.	https://www.natureworksllc.com/What-is-Ingeo https://www.total-corbion.com/ https://www.scionresearch.com/science/bio-based-products-and-technologies/biopolymers-and-chemicals
Biobased and biodegradable	Thermoplastic starch	Biotech produces BIOPLAST – thermoplastic starch from potato that is free of plasticizers. Operates on industrial scale (25000Mt/year) Argana (Austria) has several thermoplastic starch-based materials in commercial scale production.	Capital cost: High Operational cost ??			https://en.biotec.de/development/production https://www.agrana.com/produkte/alle-produktportfolios/staerke-portfolio/produkte-fuer-technische-anwendungen/biobasierte-kunststoffe
Biobased and biodegradable	PHA's made by microbial fermentation. PHV and PHB are most well-known produced by bacterial fermentation of sugars.	LCA studies show GHG and energy demand are similar to HDPE, higher than PET but lower than PS. The energy needs for the production of PHB from different raw materials. Can be home composted and degrade in marine environments. Danimer Scientific produces Nodax PHA on commercial scale (USA) using canola seed feedstock. Shenzhen Ecomann Biotechnology Co Ltd (China) commercial scale operation with annual profits *ca.* \$5million. Kaneka Corporation (Japan) industrial scale production of PHBH (5000 t/year).	Traditionally expensive to produce (EUR 2.2–5.0 /kg). Energy demand 31.5 MJ/kg GHG 0.28 kg CO2/kg material (low) Capital cost: Kaneka industrial scale plant required investment of 41 million Euros	High capital investment costs Land use for feedstock		https://danimerscientific.com/pha-beginning-of-life/ http://ecomann.sx-gear.com/introduce/ https://www.kaneka.co.jp/en/topics/news/nr20180824/
Biobased and biodegradable	Bioplastic from bloodmeal	Adurobiopolymers (NZ) manufacture Novatein A thermoplastic synthesised from bloodmeal (a co-product from abattoirs in the red meat industry).	Company claims that manufacturing involves simple processes and expect the resin to be cheaper than alternative biopolymers. Disposal costs at end-of life are expected to be lower than traditional plastics (biodegradable and home-compostable).	Not-recyclable – niche applications for current products (agriculture).	Support for scale up of onshore manufacturing. Policy support for widespread adoption in agricultural industries.	http://adurobiopolymers.com/Novatein

Material classification	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Syngas to plastic	Adapting quaternary recycling outputs to plastic (instead of energy)	Newlight Technologies make PHA from a mixture of methane and biogas from landfills and air (AirCarbon) and can convert carbon dioxide to polyurethanes and thermoplastics (first industrial scale plant in 2019. Kaneka and CJ CheilJedang are also investing in commercial production.	??	Early stage in commercial development and so are more expensive than fossil-based plastics. This could change with regulations and producer responsibility policies. Scale up has not been established.	Better option than syngas to energy – more aligned with circular economy. Investing in early scale up operations could be considered.	https://www.newlight.com/technology
Magnetic plastic		Atlaisnova (spain) has developed a magnetic additive that when applied to a material, creates better air and moisture barrier properties. Suitable for multilayer plastic products. Because of the magnetic nature of the additive, which is small and platelet-shaped particles of silicates and iron oxide, makes it easier to identify and separate the packaging at the recycling stage.	??	Pilot scale only		https://www.altaisnova.com/
Biaxially oriented polymers	Stretching method applied during processing into thin film – superior barrier and mechanical properties compared to other mono-material films.	NOVA Chemicals: Biaxially oriented polyethylene. Recyclable PE mono-material film that performs similarly to mixed-material structures. Useful for applications where multi-material plastics are used (e-commerce, food wrapping etc).	??		Potential option if phase-out of multi-material plastic film is implemented.	https://resource-recycling.com/plastics/wp-content/uploads/sites/4/2020/07/NOVA-Chem-HD-BOPE-launch-press-release-FINAL.pdf
Carbon dioxide as feedstock	Polyurethanes and polycarbonates can be directly synthesised from CO_2. Fischer-Tropsch synthesis yields synthetic naphtha which can be converted to polymers (same tech as is done with fossil naphtha).	Atmospheric CO_2 and direct air capture technologies, it is clear that atmospheric CO_2 as feedstock enables almost unlimited scalability for commodities. However, in order to be neutral or positive in Life Cycle Assessment (LCA), the chemical reduction of CO_2 has to rely on renewable energy sources three methods: (electro)chemical CO_2 reduction combined chemical–biological processes, biological CO_2 fixation. # only the direct electrochemical reduction of CO_2 enables the synthesis of fully CO_2-derived polymers.	??	Pilot/lab scale only		https://www.rutgers.edu/news/how-convert-climate-changing-carbon-dioxide-plastics-and-other-products#.XED75S2cb-Y (Blank et al., 2020; Jiang et al., 2020; Yuan et al., 2020)
Waste-to-plastic	Poultry feathers to plastic and blood meal to plastic – meat industry waste. Food waste to plastic orestry/agricultural waste to plastic	Aduro biopolymers (NZ), Scion (NZ)	Infrastructure costs for commercial scale production Valorisation of waste is appealing		Support for scale up in NZ based companies.	(Khatami et al., 2021; Mehta et al., 2021)
Edible plastic	Seaweed based material designed for food wraps, sachet and teabags that dissolves in water (zero waste) and can be consumed	Evoware – seaweed packaging that does not contain additives or plasticisers. Cultivation does not require land resources. Has a 2 year shelf-life, can be customised to give taste, colour, branding. Is printable and heat sealable. Comes in non-edible but biodegradable grade also, which can be used in packaging other products (e.g soaps). Edible cups and straws are on the market.	Price list of existing Evoware products in links. Capital cost likely to be high Operational costs ??	NZ does not have a large seaweed farming industry? Importation from Indonesia required at this point.	Seaweed farming in NZ for onshore production?	https://www.newplasticseconomy.org/innovation-prize/winners/evoware https://www.webpackaging.com/en/portals/evoware/ https://www.webpackaging.com/Up/Comp/5378/11716748/11716750-VRXBCBRG/f/Evoware-Catalogue.pdf https://www.webpackaging.com/Up/Comp/5378/11716745/11716746-XDGMDSPC/f/Price%20List%20Seaweed-Based%20Packaging.pdf

Remediation technologies

Remediation is unlikely to be a profitable venture –the business case for recycling ocean plastics depends on the collection costs, transport and logistics costs and the available recycling infrastructure and value of subsequent recyclate. Different products made from recycled plastic have different costs associated and profit margins are expected to be slim.

The benefits of remediation are obvious. Given that global implementation of every solution in existence will not stop flows of plastic to the environment and there are huge amounts of plastic already in the ocean, investment in remediation is still required to try to decrease the accumulation. Additionally, remediation presents an opportunity for quantifying plastic pollution in NZ and measuring the impact of interventions on plastic pollution quantities.

Table 7: Technologies for remediation of environmental plastic pollution

Area for remediation	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Ocean/larger freshwater systems and rivers	Clean up boats/sweeper robots (macroplastics)	Hoola One vacuums 3 gallons of sand per minute and separates microplastics by density/buoyancy. FRED (Floating Robot for Eliminating Debris), WasteShark, Jellyfishbot, Seabin, Bluephin etc. Mr Trash Wheel: operating in the Jones Fall River in Baltimore since 2014 collecting over 1600 tonnes of rubbish since inception. Powered by water wheels that use the flow of the river with back up solar panels for low-flow days. Conveyer belt transfers rubbish to bins for collection.	Collection vehicle compaction ratio, waste density, and vehicle load capacity utilisation can significantly affect the total collection costs. Distance for shipping to suitable sorting facilities is also a large cost. The annual ship purchase costs and crew costs are both adopted from the Ocean Cleanup and are respectively US$110,000 and US$140,000.	Successful implementation of such clean-up technologies relies on their technical optimisation to reduce potential adverse environmental impacts such as habitat damage, accidental capture of aquatic fauna and flora etc.		(Schmaltz et al., 2020) (van Giezen & Wiegmans, 2020) https://www.mrtrashwheel.com/
Ocean/larger freshwater systems	Sand filter (microplastics)	"Marine Microplastic Removal Tool" is a sand filter that can directly collect microplastics	??		Identify areas of high microplastic concentration and strategically implement.	https://patents.google.com/patent/US8944253B2/en
Terrestrial	Sand filters (macro plastics)	Barber Surf Rake, Barber Sand Man (microplastic)	??			http://www.hbarber.com/Cleaners/SurfRake/Default.html
Ocean water column (microplastic)	Mushroom coral	Mushroom coral are a natural sink for microplastics in the ocean (and bio-fouled microplastics) establishment of mushroom coral reefs in appropriate locations could provide a natural remediation method.	??	*D. scruposa* (most well studied) is found in the eastern and western Indian Ocean, the eastern central, northwestern and western central Pacific Ocean, Japan, the East China Sea, the Red Sea, and eastern Australia. Not native to NZ waters biosecurity risk?	Development of material with coral structure that can be used as microplastic sink in NZ waters? Exploration of NZ native corals that can be used to farm microplastics?	(Corona et al., 2020)
Rivers	The interceptor – can extract 50 000kg of trash from river per day. The Ocean Cleanup aims to install Interceptors in 1,000 of the world's most polluted rivers within five years.	Autonomous, solar powered device that uses a barrier stretching across the river to collect macro-plastic. Conveyer belts shuttle plastics to storage compartment and signals when full for boats to collect. Currently operating in Malaysia, Indonesia and Vietnam. More planned for Dominican Republic, Thialand and USA.	??	Only works for floating macroplastics.	Identify rivers with high amounts of floating microplastic pollution for strategic implementation. Ocean clean up will work with governments looking to implement to determine the best set-up for effective extraction and least interference with vessel traffic on rivers.	https://www.dezeen.com/2019/10/29/ocean-cleanup-interceptor-river-plastic-pollution/ https://theoceancleanup.com/rivers/ https://theoceancleanup.com/sources/ plastic pollution quantified in rivers can be found here – they do have data for NZ rivers.

Area for remediation	Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Rivers	Bubble barriers – macroplastics and microplastics as small as 1mm (dependent on catchment system. Works for all floating plastics and most sunken plastics.	Perforated tube laid across the bottom of canal/river. The compressed air pumped through it to create bubbles. The bubbles form a screen that catches floating debris. Operates 24/7, safe for fish and does not disrupt ship traffic. Also increases dissolved oxygen (beneficial for fish and aquatic plants.	??	NZ does not have one of the 1000 most polluted rivers, may not be a priority partner for bubble barrier.	Before implementation, bubble barrier conducts research on the preferred location alongside government and councils to ensure optimal performance.	https://thegreatbubblebarrier.com/clean-my-river/

Business-led solutions:

Reuse plastic waste (upcycling)

Product manufacture that uses recycled plastic waste is a possible business solution for the plastics crisis – consumer demand for this type of product is high.

Table 8: Technologies for reuse plastic waste (upcycling)

Technology/innovation	Specific examples/advances and commercial operation examples	Estimated costs	Key barriers to use in NZ	What would make this successful in NZ?	References and links
Micronized rubber powder	Lehigh Technologies (US) coverts old tyres and other rubber waste into micronized rubber powder that can be used for creation of new tyres, plastics, asphalt and construction materials. Lehigh serves a wide range of global markets totalling more than $10 billion in revenue.	Up to 50% lower cost per unit compared to virgin oil feedstock. each pound of MRP saves 10kWh and decreases CO_2 emissions by up to 40 percent vs synthetic rubber equivalent.	Infrastructure costs	Increased uptake of tyre collection schemes Infrastructure for converting old tyres to micronized rubber.	https://lehightechnologies.com/products_services/overview https://environment.govt.nz/what-government-is-doing/areas-of-work/waste/product-stewardship/ https://www.tyrewise.co.nz/
Roading	Macrebur, one of the pioneering companies, each km of road laid uses equivalent weight of 740 000 single-use plastic bags, each tonne of roading mix contains equivalent of 80 000 plastic bottles. Mixed plastic wastes heated with bitumen for road sealant – improves durability of the road.		Potential for more microplastic shedding from road use? Needs high temperature to melt plastics with bitumen (energy intensive, higher cost than standard practice, heat release of toxic gases from plastic materials). Oppositional to pourous asphalt implementation.	Implementation on rural roads and low/traffic flow roads that are not going to have porous asphalt.	https://www.macrebur.com/ (Schmaltz et al., 2020)
Raw material for 3D printing	3D-printing can be used to make many items from recycled plastic that otherwise would end up in landfill.	??			https://thenewraw.org/
Building material	Ecobrick: An ecobrick is a PET bottle packed solid with clean and dry used plastic. Ecobricks are made to a set density to create reusable building blocks that sequester plastic. Soft plastics recycling into fencing posts, bins buckets crates etc.	??			https://www.ecobricks.org/what/ https://www.futurepost.co.nz/
Plastic waste introduction to concrete	Concrete has a much longer service lifetime than plastic.Incorporation of plastic waste into concrete mixtures removes polymers from the waste stream for a long period of time. Polymeric residues can improve concrete properties.	??		Adding plastics to concrete manufacturing standards in NZ?	(Dijkstra et al., 2020, 2021)
Polyloom fabrics from soft plastic waste	The polyloom is a plastic weaving handloom that helps reuse and recycling of discarded plastic bags (polybags). Most monomaterial soft plastics can be used as feedstock.	Low cost for looms, medium cost for weavers and soft plastics collection.	Soft plastics collection infrastructure expansion required. Looms are hand operated (skilled personnel required) .	Scaling up soft plastics collection Business led implementation of polyloom – products made from recycled plastic have high demand.	http://atozplastics.com/upload/literature/Plastic_Weaving_Unit_Profile.asp

Table 3 Examples of products manufactured from household plastic. Source: Alba, 2011.

Plastic polymer (secondary raw material)	Product type
PP	Household articles: Bins, Buckets, boxes, crates, cradles Automobile parts Industrial: Storage solutions, transportation tools.
HDPE	Construction: Pipes, tubers, sheets, thick films, profiles Cable protection
PS	Household articles: Coat hangers, transport boxes Construction
PET	Fibres: Clothing, textiles, fabrics, car components Packaging: Bottles, films
LDPE	Films, buckets
Recycled mixed plastic	Palisades, profiles, pallets, poles

Potential phase out items and materials

Every week new products that present an alternative to a plastic item hit the market. This business led solution to the plastics issue has high consumer demand but does need some policy support to facilitate widespread adoption. As a voluntary initiative, NZ post is aiming to migrate to courier bags made of recycled LDPE (virgin LDPE is current standard).

Many alternatives exist and are accessible in NZ the issue is they can be more expensive and often consumer awareness is low.

Most nations are phasing out single use plastic items and problematic materials and the NZ proposed items and materials for phase out align with what is being done around the world

- Phase out of some PVC and polystyrene packaging products
- Plastic straws
- Plastic cotton-buds
- Drink stirrers
- Tableware (eg. plastic plates, bowls, cutlery)
- Some single-use cups and lids, made from hard-to-recycle plastics (types 3, 4, 6 and 7 or plastic lined paper cups) – excluding disposable coffee cups
- Single-use produce bags
- Non-compostable produce stickers
- Oxo-degradable plastics

Other items being phased out by different nations that NZ could consider:

- Balloons + balloon sticks
- 6-pack rings
- Single use coffee capsules'
- Tampon applicators

many countries are considering added labelling on items that have severe impact in plastics system (sanitary items, nappies, cigarette butts) to improve consumer awareness and compliance with disposal instructions

Australia national plastics plan 2021 (*National Plastics Plan 2021*) (*Action Plan for Problematic and Unnecessary Single-Use Plastic Packaging AUSTRALIAN PACKAGING COVENANT ORGANISATION*, 2020.)

Aims to phase out:

- all expanded polystyrene packaging materials (loose and moulded) by December 2022
- all PVC materials in packaging (rigid PVC and flexible labels)
- lightweight plastic shopping bags
- opaque PET bottles
- rigid plastic packaging with carbon black
- fragmentable plastics
- oxo-degradable plastics

Key research gaps:

Strategic implementation of leakage prevention and environmental remediation techs requires further knowledge regarding plastic flows in Aotearoa New Zealand.

Macroplastics:

- Quantify plastic flows in NZ.
- Industries should be incentivised to measure, monitor and report plastic use and disposal.

Microplastics:

- Evaluate microplastic abundance, distribution, plastic types and sources in the NZ environment (terrestrial, marine and fresh water).
- Optimize and implement routine automated microplastic sampling methodologies to better compare results from different study areas.
- Expand knowledge of the fate and behaviour of microplastics within the water column (e.g. in lakes), including the effects of fragmentation and biofouling.
- Develop methods to determine microplastic uptake by biota throughout the marine food web and expand the use of sentinel species to detect microplastic abundance.
- Determine the impacts (i.e. mortality, morbidity and/ or reproduction impacts) of ingested microplastics and leached plastic additives on marine biota, and better understand the transfer of this contaminant within the food chain.

Recycling techs and new materials

- There is a general lack of transparency or robust evidence base that can be used to verify claims or generate firm conclusions around the viability of many of the technologies presented in this report. This is due to the high number of smaller, lab scale examples that demonstrate possibility rather than viability.
- At the commercial scale (or close to it), the competition to be first to market is strong and this appears to limit publicly available evidence and cost information is not freely available.
- Caution must be exercised as a lack of evidence can mean either a knowledge gap or that the answer is less favourable.

References

Action Plan for Problematic and Unnecessary Single-Use Plastic Packaging AUSTRALIAN PACKAGING COVENANT ORGANISATION. (2020).

Arshad, H., Sulaiman, S. A., Hussain, Z., Naz, Y., & Basrawi, F. (n.d.). *Microwave assisted pyrolysis of plastic waste for production of fuels: a review*. https://doi.org/10.1051/matecconf/201713102005

Ashley, R., Horton, B., Lavers, T., & Mclaughlin, A.-M. (2017). *SuDS on new developments: Analysis of Evidence Final Report*. www.envpolconsulting.co.uk

Blank, L. M., Narancic, T., Mampel, J., Tiso, T., & O'Connor, K. (2020). Biotechnological upcycling of plastic waste and other non-conventional feedstocks in a circular economy. In *Current Opinion in Biotechnology* (Vol. 62, pp. 212–219). Elsevier Ltd. https://doi.org/10.1016/j.copbio.2019.11.011

Corona, E., Martin, C., Marasco, R., & Duarte, C. M. (2020). Passive and Active Removal of Marine Microplastics by a Mushroom Coral (Danafungia scruposa). *Frontiers in Marine Science*, *7*, 128. https://doi.org/10.3389/fmars.2020.00128

Craig, I. H., & White, J. R. (2005). Crystallization and chemi-crystallization of recycled photodegraded polyethylenes. *Polymer Engineering and Science*, *45*(4), 588–595. https://doi.org/10.1002/pen.20314

Dijkstra, H., van Beukering, P., & Brouwer, R. (2020). Business models and sustainable plastic management: A systematic review of the literature. *Journal of Cleaner Production*, *258*, 120967. https://doi.org/10.1016/j.jclepro.2020.120967

Dijkstra, H., van Beukering, P., & Brouwer, R. (2021). In the business of dirty oceans: Overview of startups and entrepreneurs managing marine plastic. *Marine Pollution Bulletin*, *162*, 111880. https://doi.org/10.1016/j.marpolbul.2020.111880

Ding, K., Liu, S., Huang, Y., Liu, S., Zhou, N., Peng, P., Wang, Y., Chen, P., & Ruan, R. (2019). Catalytic microwave-assisted pyrolysis of plastic waste over NiO and HY for gasoline-range hydrocarbons production. *Energy Conversion and Management*, *196*, 1316–1325. https://doi.org/10.1016/j.enconman.2019.07.001

Ellis, J. B., Shutes, R. B. E., & Revitt, M. D. (2003). *Constructed Wetlands and Links with Sustainable Drainage Systems*.

Fitzgerald, B., & Bird, W. S. (2011). *Stormwater Technical Specialist Manager Development and Technical Services Stormwater Organisation: Auckland Council Organisation: Auckland Council Gross Pollutant Traps as a Stormwater Management Practice-Literature Review: Prepared for Auckland Council Contents*.

Gent, M. R., Menendez, M., Toraño, J., & Diego, I. (2009). Recycling of plastic waste by density separation: Prospects for optimization. In *Waste Management and Research* (Vol. 27, Issue 2, pp. 175–187). SAGE PublicationsSage UK: London, England. https://doi.org/10.1177/0734242X08096950

Gere, D., & Czigany, T. (2020). Future trends of plastic bottle recycling: Compatibilization of PET and PLA. *Polymer Testing*, *81*, 106160. https://doi.org/10.1016/j.polymertesting.2019.106160

Hann, S., & Connock, T. (2020). *Chemical Recycling: State of Play Report for CHEM Trust*. www.eunomia.co.uk

Hatano, M., Tabata, Y., Yoshida, Y., Toh, K., Yamashita, K., Ogura, Y., & Ishihara, K. (2018). Metal-free transesterification catalyzed by tetramethylammonium methyl carbonate. *Green Chemistry*, *20*(6), 1193–1198. https://doi.org/10.1039/c7gc03858e

Hou, L., Kumar, D., Yoo, C. G., Gitsov, I., & Majumder, E. L. W. (2021). Conversion and removal strategies for microplastics in wastewater treatment plants and landfills. *Chemical Engineering Journal*, *406*. https://doi.org/10.1016/j.cej.2020.126715

Iyare, P. U., Ouki, S. K., & Bond, T. (2020). Microplastics removal in wastewater treatment plants: A critical review. In *Environmental Science: Water Research and Technology* (Vol. 6, Issue 10, pp. 2664–2675). Royal Society of Chemistry. https://doi.org/10.1039/d0ew00397b

Jian, J., Xiangbin, Z., & Xianbo, H. (2020). An overview on synthesis, properties and applications of poly(butylene-adipate-co-terephthalate)–PBAT. *Advanced Industrial and Engineering Polymer Research*, *3*(1), 19–26. https://doi.org/10.1016/j.aiepr.2020.01.001

Jiang, L., Gonzalez-Diaz, A., Ling-Chin, J., Malik, A., Roskilly, A. P., & Smallbone, A. J. (2020). PEF plastic synthesized from industrial carbon dioxide and biowaste. *Nature Sustainability*, *3*(9), 761–767. https://doi.org/10.1038/s41893-020-0549-y

Karaagac, E., Koch, T., & Archodoulaki, V. M. (2021). The effect of PP contamination in recycled high-density polyethylene (rPE-HD) from post-consumer bottle waste and their compatibilization with olefin block copolymer (OBC). *Waste Management*, *119*, 285–294. https://doi.org/10.1016/j.wasman.2020.10.011

Khatami, K., Perez-Zabaleta, M., Owusu-Agyeman, I., & Cetecioglu, Z. (2021). Waste to bioplastics: How close are we to sustainable polyhydroxyalkanoates production? In *Waste Management* (Vol. 119, pp. 374–388). Elsevier Ltd. https://doi.org/10.1016/j.wasman.2020.10.008

Klingelhöfer, D., Braun, M., Quarcoo, D., Brüggmann, D., & Groneberg, D. A. (2020). Research landscape of a global environmental challenge: Microplastics. *Water Research*, *170*, 115358. https://doi.org/10.1016/j.watres.2019.115358

Kumar, A., Dash, S. K., Ahamed, M. S., & Lingfa, P. (2020). Study on Conversion Techniques of Alternative Fuels from Waste Plastics. In *Energy Recovery Processes from Wastes* (pp. 213–224). Springer Singapore. https://doi.org/10.1007/978-981-32-9228-4_18

Ludlow-Palafox, C., & Chase, H. A. (2001). Microwave-induced pyrolysis of plastic wastes. *Industrial and Engineering Chemistry Research*, *40*(22), 4749–4756. https://doi.org/10.1021/ie010202j

Mastellone, M. L. (2020). Technical description and performance evaluation of different packaging plastic waste management's systems in a circular economy perspective. *Science of the Total Environment*, *718*, 137233. https://doi.org/10.1016/j.scitotenv.2020.137233

Mehta, N., Cunningham, E., Roy, D., Cathcart, A., Dempster, M., Berry, E., & Smyth, B. M. (2021). Exploring perceptions of environmental professionals, plastic processors, students and consumers of bio-based plastics: Informing the development of the sector. *Sustainable Production and Consumption*, *26*, 574–587. https://doi.org/10.1016/j.spc.2020.12.015

Miandad, R., Rehan, M., Barakat, M. A., Aburiazaiza, A. S., Khan, H., Ismail, I. M. I., Dhavamani, J., Gardy, J., Hassanpour, A., & Nizami, A.-S. (2019). Catalytic Pyrolysis of Plastic Waste: Moving Toward Pyrolysis Based Biorefineries. *Frontiers in Energy Research*, *7*(MAR), 27. https://doi.org/10.3389/fenrg.2019.00027

Moores, J. (2011). *THE INFLUENCE OF ROAD SURFACE CHARACTERISTICS ON RUNOFF QUALITY*.

National Plastics Plan 2021. (2021). www.environment.gov.au/plastics-and-packaging

Neidel, T. L., & Jakobsen, J. B. (2013). *Plastic ZERO-Public Private Cooperations for Avoiding Plastic as a Waste: Report on assessment of relevant recycling technologies*.

Nikiema Josiane, Mateo-Sagasta Javier, Asiedu Zipporah, Dalia Saad Dalia, L. B. (2020). *Water pollution by plastics and microplastics: A review of technical solutions from source to sea | UNEP - UN Environment Programme*. https://www.unep.org/resources/report/water-pollution-plastics-and-microplastics-review-technical-solutions-source-sea

Norin, H., & Ab, E. (2018). *Microplastics from industrial laundries-A laboratory study of laundry effluents Microplastics from industrial laundries*.

Nzta. (2011). *Research Report 455. Performance of open graded porous asphalt in New Zealand*.

Reichert, C. L., Bugnicourt, E., Coltelli, M.-B., Cinelli, P., Lazzeri, A., Canesi, I., Braca, F., Martínez, B. M., Alonso, R., Agostinis, L., Verstichel, S., Six, L., Mets, S. De, Gómez, E. C., Ißbrücker, C., Geerinck, R., Nettleton, D. F., Campos, I., Sauter, E., … Schmid,

M. (2020). Bio-Based Packaging: Materials, Modifications, Industrial Applications and Sustainability. *Polymers*, *12*(7), 1558. https://doi.org/10.3390/polym12071558

Rogers, K.M., Turnbull, J.C., Dahl, J., Phillips, A., Bridson, J., Raymond, L.G., Liu, Z., Yuan, Y.,Hill, S. J. . (2015). Authenticating bioplastics using carbon and hydrogen stable isotopes – An alternative analytical approach. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *53*(9), 1689–1699. https://doi.org/10.1002/rcm.9051

Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., Virdin, J., & Dunphy-Daly, M. M. (2020). Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. In *Environment International* (Vol. 144). Elsevier Ltd. https://doi.org/10.1016/j.envint.2020.106067

Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment*, *42*(11), 3830–3836. https://doi.org/10.1016/j.buildenv.2006.11.016

Shahnawaz, M., Sangale, M. K., Ade, A. B., Shahnawaz, M., Sangale, M. K., & Ade, A. B. (2019). Plastic Waste Disposal and Reuse of Plastic Waste. In *Bioremediation Technology for Plastic Waste* (pp. 21–30). Springer Singapore. https://doi.org/10.1007/978-981-13-7492-0_3

Shang, J., Chai, M., & Zhu, Y. (2003). Photocatalytic degradation of polystyrene plastic under fluorescent light. *Environmental Science and Technology*, *37*(19), 4494–4499. https://doi.org/10.1021/es0209464

Sheldon, R. A., & Norton, M. (2020). Green chemistry and the plastic pollution challenge: Towards a circular economy. In *Green Chemistry* (Vol. 22, Issue 19, pp. 6310–6322). Royal Society of Chemistry. https://doi.org/10.1039/d0gc02630a

Singh, S. K., Zeddies, M., Shankar, U., & Griffiths, G. A. (2019). Potential groundwater recharge zones within New Zealand. *Geoscience Frontiers*, *10*(3), 1065–1072. https://doi.org/10.1016/j.gsf.2018.05.018

Sol, D., Laca, A., Laca, A., & Díaz, M. (2020). Approaching the environmental problem of microplastics: Importance of WWTP treatments. In *Science of the Total Environment* (Vol. 740). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2020.140016

Solis, M., & Silveira, S. (2020). Technologies for chemical recycling of household plastics – A technical review and TRL assessment. In *Waste Management* (Vol. 105, pp. 128–138). Elsevier Ltd. https://doi.org/10.1016/j.wasman.2020.01.038

Transport Agency, N. (2010). *Stormwater Treatment Standard for State Highway Infrastructure (May 2010)*. www.nzta.govt.nz

van Giezen, A., & Wiegmans, B. (2020). Spoilt - Ocean Cleanup: Alternative logistics chains to accommodate plastic waste recycling: An economic evaluation. *Transportation Research Interdisciplinary Perspectives*, *5*, 100115. https://doi.org/10.1016/j.trip.2020.100115

Vogelsang, C., Lusher, A., Dadkhah, M. E., Sundvor, I., Umar, M., Ranneklev, S. B., Eidsvoll, D., & Meland, S. (2019). Microplastics in road dust – characteristics, pathways and measures. *7361*. https://toi.brage.unit.no/toi-xmlui/handle/11250/2670146

Vollmer, I., Jenks, M. J. F., Roelands, M. C. P., White, R. J., Harmelen, T., Wild, P., Laan, G. P., Meirer, F., Keurentjes, J. T. F., & Weckhuysen, B. M. (2020). Beyond Mechanical Recycling: Giving New Life to Plastic Waste. *Angewandte Chemie International Edition*, *59*(36), 15402–15423. https://doi.org/10.1002/anie.201915651

Yuan, X., Lee, J. G., Yun, H., Deng, S., Kim, Y. J., Lee, J. E., Kwak, S. K., & Lee, K. B. (2020). Solving two environmental issues simultaneously: Waste polyethylene terephthalate plastic bottle-derived microporous carbons for capturing CO2. *Chemical Engineering Journal*, *397*, 125350. https://doi.org/10.1016/j.cej.2020.125350