WENDY TUCKERMAN MP		**OBJECT**	Submission ID: 218317
Organisation:	*Local constituents*	Key issues:	*Social impacts,Visual impacts, design and landscaping,Land use compatibility (surrounding land uses),Traffic,Other issues*
Location:	*New South Wales 2580*		
Attachment:	*Attached overleaf*		

Submission date: 11/25/2024 2:47:25 PM

Independent Planning Commission

Level 15, 135 King Street

Sydney NSW 2000

Moss Vale Plastics Recycling Facility

SSD-9409987

Dear Commissioners

25 November 2024

Submission " Moss Vale Plastics Recycling Facility

Dear Commissioners,

On behalf of the community of Moss Vale, I provide this submission objecting to the approval of the Moss Vale Plastics Recycling Facility (SSD 9409987).

There are significant concerns on the impacts of such a development " across environmental, social and economic grounds. Specifically, these concerns relate to:

Adequacy of the assessment to enable the Commission to properly determine the application, noting:

The absence of information to appropriately address the required matters for consideration under s4.15 of the EP&A Act.

The requirement to condition the development as proposed to ensure it achieves the objective of minimising impact, rather than being able to rely on the merits of the application as it stands.

Adequacy of the provided assessment documentation in addressing expected content o objectively inform a determination, noting:

application of the principles of Ecologically Sustainable Development.

fire risk (process and bushfire).

impacts on local and regional noise, air, water and soil quality and contamination.

the lack of consideration and assessment on impacts generated by microplastics.

the inadequate Development alternatives assessment "limited consideration of site alternatives and no consideration of treatment train alternatives.

ambiguity around operational procedures relating to the duration of time roller doors are open, how the identified timing (50 seconds) can be achieved, and subsequent impacts on air quality.

inadequate assessment around both direct and indirect impacts resulting from the Development.

One of our local constituents has commissioned a third-party review of the EIS and supportive assessment documentation. We provide the outcomes of their review attached to this submission, for your consideration.

Should you have any queries, please do not hesitate to contact me on 02 4822 6444

Yours sincerely,

Wendy Tuckerman MP

Member for Goulburn

Shadow Minister for Local Government

THE HON. WENDY TUCKERMAN MP
MEMBER FOR GOULBURN

25 November 2024

Independent Planning Commission
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Sydney NSW 2000

Moss Vale Plastics Recycling Facility
SSD-9409987

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[redacted]

Wendy Tuckerman MP

Member for Goulburn

Shadow Minister for Local Government

IPC Submission Moss Vale Plastics Recycling Facility (Case 09)

ASPECT

November 2024

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Should additional information become available which may affect the opinions expressed in this report Aspect Environmental Pty Ltd reserves the right to review such information and if warranted to modify the opinions accordingly.

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Checker Richard Johnson

Approver Richard Johnson

Date 25/11/2024

Report No. J001998241125.02

Revision Rev 2

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Revisions

Revision	Date	Description	Prepared by	Approved by
1	22/11/2024	Issue to C ent	Ca t n Johnson Megan Kove s R chard Johnson	R chard Johnson
2	25/11/2024	F na	Ca t n Johnson	R chard Johnson

Contents

Appendices

Glossary

Term	Definition
DAF	d sso ved a r f otat on
DPHI	Department of P ann ng Hous ng and Infrastructure (NSW)
EIS	Env ronmenta Impact Statement (GHD, January 2022)
EP&A Act	*Environmental Planning and Assessment Act 1979* (NSW)
EPA	Env ronment Protect on Author ty
ESD	eco og ca y susta nab e deve opment
IPC	Independent P ann ng Comm ss on
LGA	oca government area
MV WWTP	Moss Va e Wastewater Treatment P ant
NHMRC	Nat ona Hea th and Med ca Research Counc
NSW MMP	NSW M crop ast cs Mon tor ng Program
PFAS	Perf uoroa ky and Po yf uoroa ky Substances
RtS	Response to Subm ss ons
SSD	State s gn f cant deve opment
WHO	Wor d Hea th Organ sat on

Executive Summary

The following report provides a review of the EIS, its supporting documentation, and DPHI's Assessment Report in relation to the issuing of consent for State significant development application (SSD) SSD-9409987 – Moss Vale Plastics Recycling Facility.

The review supports an objection to the application, raised under two primary heads as follows:

1. Questions around the adequacy of the Department of Planning Housing and Infrastructure's (DPHI) effecting assessment processes as required under the *Environmental Planning and Assessment Act 1979* (EP&A Act), specifically how DPHI has appropriately or adequately considered:
    a. matters for consideration; and
    b. proposed conditioning of any approval
2. Adequacy of the provided assessment
    a. Address of required EIS documentation, as specified by section 192 of the *Environmental Planning and Assessment Regulation 2021* ; and
    b. Potential misrepresentation of the project and potential impacts

The following content provides further discussion in respect of these heads of objection, with supporting documentation and reference material provided as Appendices.

We trust that the Independent Planning Commission will give due consideration to the issues raised and review the Proponent's and Department's submissions regarding this application accordingly.

1 Adequacy of DPHI Assessment of SSD Application / EIS

It is our position, on review of the DPHI assessment report (*Moss Vale Plastics Refining Facility State Significant Development Assessment Report (SSD-9409987)* (DPHI, October 2024)), that the Department's assessment does not satisfactorily present a valid assessment of the application in line with s4.15 of the EP&A Act with respect to matters for consideration, and has presented draft conditions of consent which, in effect, condition the development to have a lesser impact than that which the development presented and applied for, essentially changing the development as applied for to enable its approval. It is our view that to satisfactorily address the matters for consideration under s4.15, the IPC would need to further modify the development to achieve the stated objectives of minimising impact to the environment and social health.

These issues are discussed, with reference to the DPHI Assessment Report (DPHI, October 2024) and the Proponent's EIS and supporting documentation.

1.1 Matters for Consideration – S4.15 EP&A Act

Section 4.15 identifies the evaluation process for determining development applications. Section 4.15(1) of the EP&A Act identifies the matters a determining authority is to take into consideration in determining a development application. Section 4.15(1)(b) requires the consideration of:

> *(b) the likely impacts of that development, including environmental impacts on both the natural and built environments, and social and economic impacts in the locality,*

Critical to the ability of the relevant consent authority to consider likely impacts of the development is that the likely impacts are adequately presented in the provided EIS and supporting documentation.

1.1.1 Microplastics

The impacts, and potential impacts, associated with microplastics pollution have been documented in technical fora and public media forum in the last 3-5 years (**Appendix A**). Issues and impacts associated with plastic recycling are known to include:

- Air Pollution: Emissions from energy use and plastic dust.
- Water Contamination: Risk of releasing microplastics into water sources. Microplastics can also be a vector, or vehicles, for other water contaminants, including PFAS/FOS.
- Microplastic Spread: Long-term environmental impact, particularly in aquatic ecosystems.
- Community Health: Health impacts on workers from plastic dust exposure.
- Fire Risk: Production and distribution mechanism for microplastics to air, land and water.
- Social Impact: Potential for job creation, but also risk of environmental degradation affecting communities.

Nowhere in the EIS body are the terms "microplastics" or "plastic dust" used. They were noted in community engagement sessions documented in Appendix E of the EIS, but excluded from the risk assessment in Appendix F.

While the issue was raised in the Response to Submissions (RtS) by submitters (including Council), the Proponent's response relies on reverting to the EIS content, specifically, the provision of a dissolved air flotation (DAF) wastewater treatment process, with dewatered filter cakes being disposed of to landfill. There is a reliance on functionality of the local council wastewater treatment plant to remove residual microplastics that escape its DAF treatment process. There is no further quantitative, meaningful, consideration of actual risk, likelihood or consequence of occurrence. There is a marked absence of content that would be critical to enable the matter to be considered fully and appropriately.

The proposed development is reliant on the installation of an on-site wastewater treatment facility (DAF), with the Council wastewater treatment plant future upgrades being relied on as a backup treatment for wastewater discharged as trade waste. There is no discussion on the effectiveness, or otherwise of DAF. A summary discussion on effectiveness of DAF systems for microplastics is presented as **Appendix B**.

The Proponent's reliance on a DAF treatment system and intended deferred mitigation to the future development of Council's wastewater treatment plant demonstrates the absence of effective assessment and mitigation of a material risk and direct impact of the proposed development. It raises further concerns in terms of an absence of consideration of process alternatives together with a justification of the selected alternative.

Recent assessment of the removal of microplastics from recycled plastics process water (L. Dayal et al., 2024[1]; Romphophak et al.; 2024[2]) illustrate that removal efficiency is improved by systems that implement a series of treatment steps that includes disinfection, filtration and biological treatment following physical treatment, such as DAF processes (Figure 1-1).

[1] Dayal, L et al. "Recent advancement in microplastic removal process from wastewater – A critical review." The Journal of Hazardous Materials Advances vol. 16 (2024): 100460.
[2] Romphophak, P et al. "Removal of microplastics and nanoplastics in water treatment processes: A systematic literature review." The Journal of Water Process Engineering vol. 64 (2024): 105669.

Figure 1-1 Implementation of DAF as a component part of a treatment train process for effective removal of microplastics from process water (Source: L. Dayal et al., 2024[3]).

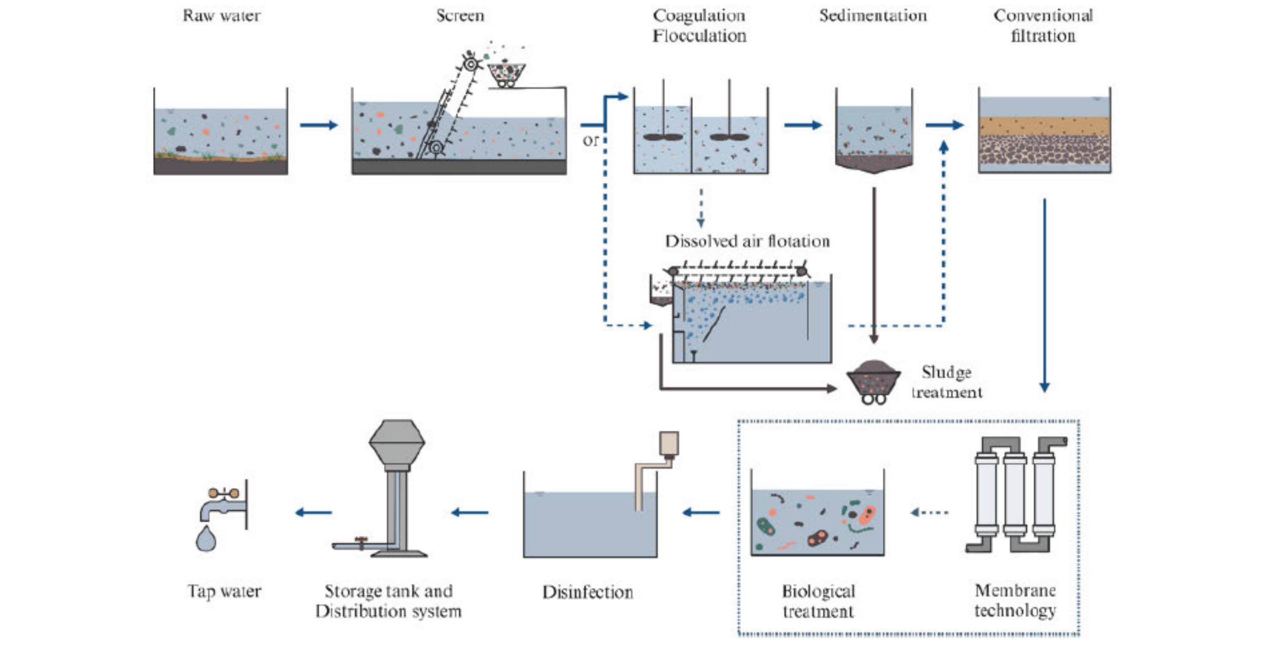


Fig. 6. Schematic diagram of water treatment processes applied in the reviewed studies: the solid line is the main processes, the dash line represents alternative process of CFS, and the optional processes for drinking/water treatment are enclosed in the dotted square.

These assessments recommend that application of additional treatment steps should be considered during the decision-making process for effecting microplastic removal by any proposed operation.

There is no demonstrated consideration within the EIS content that any alternative or additional treatment train processes, beyond DAF, have been considered to optimise or improve the efficacy of microplastic removal at source, or in downstream Council treatment processes, following discharge as trade waste.

The EIS identifies that 10KL/day of process wastewater would be discharged to the Moss Vale Wastewater Treatment Plant (MV WWTP) under a trade waste agreement, for further processing and treatment. Council have indicated that the MV WWTP is scheduled for augmentation by 2026 to cater primarily for growth and associated hydraulic capacity.

In correspondence dated 8 March 2024 to GHD, the Council clearly identify that *'no specific treatment mechanism for microplastic removal'* is proposed as part of this. The WWTP capacity to remove microplastics would remain to form part of the settlement of biosolids – rather than there being any proposed targeted treatment. The Council note that any remaining plastics that bypass this process would eventually make their way to the environment in treated effluent – as is common across Australia.

Based on the design load of the WWTP – Council identifies the Plas Refine wastewater could double Council's microplastic loading as a worst-case scenario.

Given the complete removal of microplastics from wastewater is not yet possible, the Council note, together with national and global organisations (e.g. World Health Organisation (WHO)),

[3] Dayal, L et al. "Recent advancement in microplastic removal process from wastewater – A critical review." The Journal of Hazardous Materials Advances vol. 16 (2024): 100460.

recommend that industrial sources of microplastics should be addressed **at source** and not pass the responsibility on to the Council and, indirectly, pass a cost burden to the local community in part-resolution of a regional issue.

Response to submissions (RtS) Appendix J, section 4.4 talks to microplastics in the context of air quality and odour. It is stated in the RtS that emissions of fine particulate matter to the atmosphere would comply with NSW Clean Air Regulation standards of concentration. The cumulative impact assessment for particulate matter predicts that there would be no exceedances of NSW EPA criteria at any residential location but there would be a minor exceedance of at the nearest commercial receptor if background levels were unusually high.

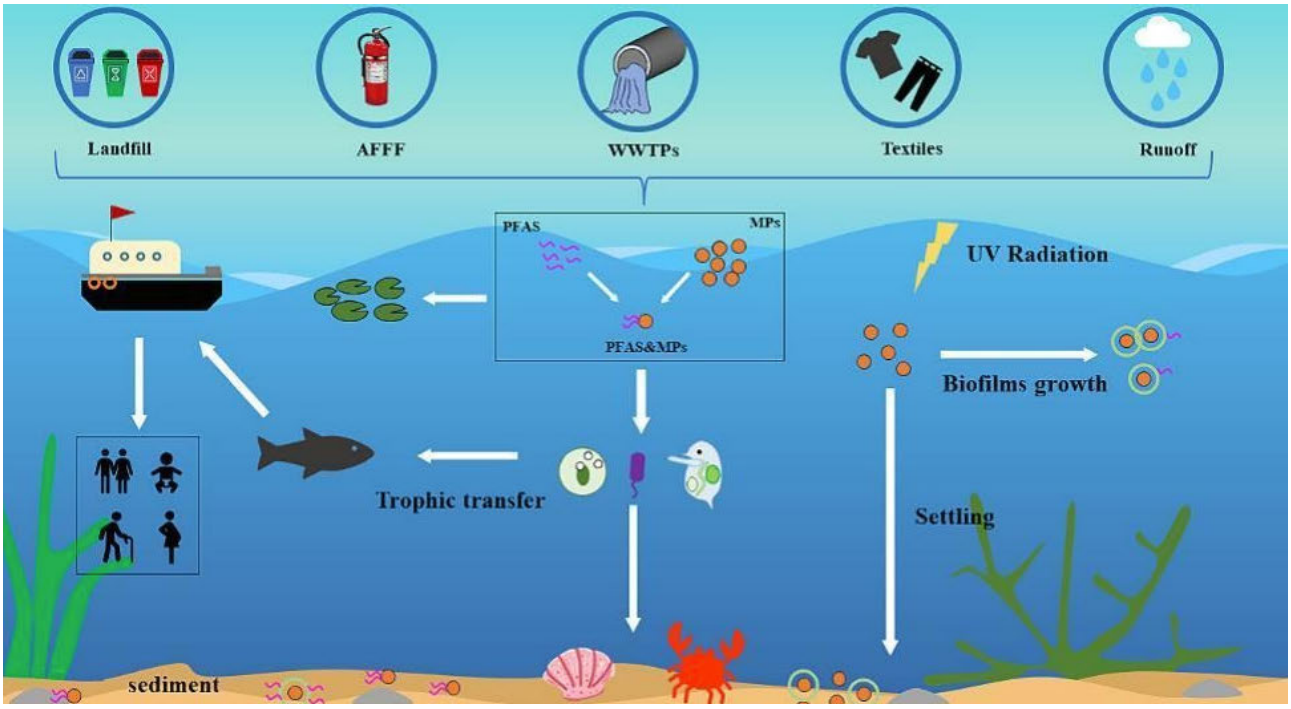
It should be noted that there are presently no criteria specific to microplastics for discharge to water (including wastewater), to air (other than bundled within $PM_{2 5}$ particulate considerations), or to land.

With respect to Australian drinking water guidelines, the National Health and Medical Research Council (NHMRC) has recommended that research and development should be directed, at least in part, towards increasing the understanding of emerging water quality issues and the relationship between public health outcomes and water quality. There is currently limited evidence of the impacts of contaminants such as microplastics on human health. In such circumstances, the NHMRC's Australian Drinking Water Guideline 2011 (as updated in 2022) recommends that a precautionary approach be taken. To allow evaluation of the risk to public health posed by emerging problems, the NHMRC identify the key role of long-term evaluation as an important due-diligence mechanism. The NHMRC identify the importance of the quality of *source water* and note that prevention of contamination provides greater surety than removal of contaminants by treatment, so the most effective barrier is protection of source waters to the maximum degree practicable (NHMRC, 2022 page 3).

It is worth noting that PFAS (the 'forever' chemical) while being a separate substance, has been identified by the NHMRC as having the potential to be present as a residue or contaminant in microplastics (https://www.nhmrc.gov.au/health-advice/environmental-health/water/PFAS-review/questions-and-answers). This coexistence can create conditions where they interact and combine toxicity (Figure 1-2). In addition to circumstances in which microplastics contain PFAS themselves, microplastics can also behave as a vector for PFAS and its wider distribution in the environment (Yu et al, 2024[4]).

[4] Yu, Fan et al. "Interaction of microplastics with perfluoroalkyl and polyfluoroalkyl substances in water: A review of the fate, mechanisms and toxicity." The Science of the total environment vol. 948 (2024): 175000.

Figure 1-2 Interaction of PFAS and microplastics (MP in above) within the environment (Source: Yu et al, 2024[5]).



The NSW Microplastics Monitoring Program (NSW MMP) tracks microplastics in marine and estuarine environments, they do not yet enforce specific environmental criteria or health-based thresholds. No consideration has been provided of how the proposed development has considered NHMRC recommendations or considers, or incorporates, objectives and findings from the NSW MMP.

Australia relies heavily on voluntary bans and monitoring. Criteria for microplastics in drinking water and seafood are under study, with no enforceable limits established. This position is masked by the Proponent's identification of "no exceedances of criteria" within the EIS documentation.

An overview of the global and local consideration of the risk and regulation of microplastics is presented within **Appendix A**.

Europe has been setting restrictions for microplastics in products and monitoring drinking water but is still researching health-based thresholds. The United States has State-level initiatives, like California's monitoring program, but lacks enforceable federal thresholds.

Setting quantifiable environmental and health-based thresholds for microplastics remains a global and local challenge, as ongoing research seeks to establish their impact on ecosystems and human health. The implication that discharges meet local regulatory criteria belies the fact that there are no specific criteria, as yet, pertaining to managing the risk of microplastics to human health and to the environment.

In the absence of a robust discussion and assessment of the potential risks that microplastics present to human health and the environment, it is difficult to see how DPHI could have adequately assessed the likely impacts of the development.

[5] Yu, Fan et al. "Interaction of microplastics with perfluoroalkyl and polyfluoroalkyl substances in water: A review of the fate, mechanisms and toxicity." The Science of the total environment vol. 948 (2024): 175000.

1.1.2 Principles of Ecologically Sustainable Development

The principles of ecologically sustainable development (ESD) are to be applied when decisions are being made under any legislative enactment or instrument which adopts the principles[6].

The EP&A Act is a relevant legislative enactment. It expressly states, at s 1.3(b), that one of the objects of the EP&A Act is to encourage ecologically sustainable development. The Act defines ecologically sustainable development as having the same meaning as it has in s 6(2) of the *Protection of the Environment Administration Act (1991).*

The principles of ESD to be considered, and how they are relevant to the consideration of the proposed development are:

- The precautionary principle: appropriate consideration of the risks of microplastics to human health and to the environment. Reflection on global incidents at plastics refineries and adoption of an appropriate standard of risk and hazard prevention.
- Intergenerational equity: The proposed development claims to be diverting 120,000t/year of plastics from landfill. In effecting this diversion, the development is concurrently generating a waste issue by creating new process-driven waste streams that would not exist but for the development.

  The proposed development is identified as generating the following waste streams:

  – 10,000 t/yr non-renewables – goes to landfill

  – 9,000 t/yr sludge from wastewater – goes to landfill

  – 1,800 t/yr filter residue – landfill

  – 288,000 KL/yr wastewater – reused onsite for washing plastics (incrementally discharged as usability declines)

  – 10 KL/day (365 KL/year) – sewer discharge

  This creates an impact on local waste management (including landfill facilities) that would not otherwise exist, shortening the operational life of the facilities in their current state or forcing an augmentation earlier than would otherwise be required.

  What is unstated in the EIS is that recycled plastic products are, generally unable to be recycled again, so they will ultimately end up as landfill waste[7]. That is to say, the 120,000t/year of "diverted" plastics, is only temporarily diverted, and is simply deferring the landfill demand for future generations or relying on a "fictional" future technology to resolve the problem.

  The Proponent is proposing to utilise potable water sourced from town mains (beyond rainwater capture) as part of its process water stream. Potable water is a finite resource within the local government area (LGA). The proposed development represents a real constraint on the progressive social development of the Moss Vale community by limiting availability of potable water to support residential and commercial growth.

  The operating period of the recycling facility is identified as being 25 years, despite the infrastructure having a stated functional life of 50 years. The valuation of a 25-year operational

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[6] *Telstra Corporation Ltd v Hornsby Shire Council* [2006] NSWLEC 133 (2006) 67 NSWLR 256; *Minister for Planning v Walker [2008] NSWCA 224*.

[7] https://stories.undp.org/why-arent-we-recycling-more-plastic ; https://www.theguardian.com/us-news/2024/feb/15/recycling-plastics-producers-report.

life prior to decommissioning and the purported benefit of “diverted” plastics compared with decommissioning costs (financial, tangible and intangible – including emissions costs and values associated with materials cleanup and disposal) is absent from the assessment. It is left to some nominal future state to resolve. It ignores the end-life cost of disposal of plastic products generated by the facility during its life, presumably to landfill.

- Conservation of biological integrity: requires consideration and assessment of the potential biological risks to discharge of microplastics to land and river systems. Noting in this case the site positioning within the catchment of Wingecarribee Reservoir and Sydney’s drinking water catchment.
- Improved valuation and pricing mechanisms:
  - Polluter pays principles
  - Payment of prices based on full life cycle – including use of natural resources, assets and ultimate disposal of any waste
  - Establishing incentive structures and market mechanisms to enable those best placed to solve their own solutions and responses to environmental problems

  Noting the

  - absence of quantification of the potential risks of microplastics to human health and the environment;
  - absence of valuation of potable water demand;
  - absence of valuation of energy demand costs;
  - deferral of wastewater treatment costs to Local Council prospective MV WWTP upgrades, which does not have present demonstrated capacity to effectively treat Plas Refine contaminated wastewater;
  - absence of valuation processes for the immediate and long-term management of waste streams (including end-product disposal to landfill);
  - deferred evaluation of full costs of decommissioning; and
  - absence of a nett environmental benefit assessment of proceeding with the proposed development versus not proceeding with it

It is difficult to see how the Proponent has provided sufficient information to enable any consent authority to affect its obligations under s 4.15(1)(b) of the EP&A Act in respect of the principles of ESD.

1.1.3 Conditioning the Consent to Enable Consent Authority Approval

Draft conditions of consent need to align to the DPHI *Guide to Writing Conditions of Consent* (August 2024). Conditions requiring minor design changes should only be used to redesign minor aspects of the development. Conditions should not be used as a solution to make a proposed development worthy of consent, instead the merit of the development application and whether it should be approved should be questioned.

Equally conditions must be certain and achievable.

On review of the draft conditions, the following are identified as being questionable in terms of deferring actual assessment of impact or mitigative need,

- B43 – Air Quality Discharges

  The Proponent must install and operate equipment in line with best practice to ensure that the development complies with all load limits, air quality criteria/air emission limits and air quality monitoring requirements as specified in the EPL applicable to the site. The installed equipment must be able to be retrofitted or upgraded.

  The realistic and practicable achievement of B34 is constrained in the absence of any meaningful regulatory performance criteria in respect of microplastics, despite their express reference in B44.

- B44

  (b) detail and rank all emissions from all sources of the development, including particulate emissions ***and microplastics***;

  (c) identify the control measures that will be implemented for each emission source

There is an absence of any monitoring requirements or performance expectations for the protection of biodiversity during operation, despite the documented risk of microplastics to the aquatic ecosystem and drinking water catchments in either a general process or emergency response (fire) sense.

The draft conditions of consent point to DPHI being aware of the social and environmental risks associated with microplastics. However, any serious consideration of the potential impacts arising from the proposed development in both overcoming the shortfall in the EIS assessment documentation has been deferred from the assessment consideration by prescribing the assessment and control measures to be part of the Air Quality Management Plan.

Further, DPHI has ignored the absence of regulatory performance criteria in respect of water quality discharge and accumulation in the biological environment, without similar recognition of the absence of consideration and certainty within the EIS.

To adequately achieve the objects of the EP&A Act, the proposed development would need to be conditioned to install additional wastewater treatment processes, comprising at a minimum a reverse osmosis or ultrafiltration technology. This type of condition would be required to enable the proposed development to be (in this respect) “worthy of consent”. However, this type of condition conflicts with the Department’s Guidelines, which compel consideration of the merits of the application and whether it is fit to be approved.

2 Adequacy of the EIS Assessment

On review of the Proponent's EIS documentation the following observations are made:

2.1 Project Description

- The project description does not address the full life-cycle of the project. The proposed development is represented as diverting waste plastic from landfill. However, plastic products cannot be recycled more than once, meaning they will end up as landfill at a later point in time. Recycled plastics are not being diverted from landfill, the need for them to be disposed of to landfill is simply being deferred.
- No justification is provided as to why the proposed development has a functional life of 25 years, while the plant and infrastructure has an operational life identified as 50 years. There is no valuation attributed to the decommissioning of plant and equipment, and the loss of resource recovery, 25 years in advance of its operational life.
- The waste stream calculations may be distorting the water consumption requirements. Referenced sources[8] identify recycling facilities utilise 3.48kg of water used per 1kg of recycled plastic. 120,000t of recycled plastic/year equates to 417,600kL of water per year. Which is substantially greater than the identified 288,000kL of wastewater generated, and assumedly has an equally greater demand on potable water requirement to supplement reclaimed process water. Further independent confirmation of water demand and wastewater generation impacts is required.
- Similarly, the EIS does not provide an energy balance for the project. While it identifies that recycling plastics is less energy intensive than production of virgin plastic, it is still an energy intensive process. The prospective energy demand for the site may introduce additional transmission, supply and infrastructure provision as an indirect impact that may also have direct impacts of its own.
- The project description fails to identify or quantify nature and scale of microplastics and plastic dust generation[9].

2.2 Consideration of Alternatives

It is viewed that the consideration of alternatives in the EIS document is deficient and does not represent a robust and meaningful consideration of Project alternatives.

What has been provided is focussed on a scant overview of alternative site locations, various road access arrangements and building layout options. There is no robust review of site locations, demonstrated consideration of alternative treatment train options – and so no demonstration that the Project provides the best outcome on the balance of social, economic and environmental factors.

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[8] Beata Jabłońska, Water consumption management in polyethylene terephthalate (PET) bottles washing process via wastewater pretreatment and reuse, Journal of Environmental Management, Volume 224, 2018, Pages 215-224

[9] Singh, N., Walker, T.R. Plastic recycling: A panacea or environmental pollution problem. *npj Mater. Sustain.* **2**, 17 (2024).

2.2.1 Site Location Assessment

The presented consideration provides no comparative assessment of locations to demonstrate a valid consideration was made. The Proponent's EIS has literally jumped from western Sydney, in a general sense, to preferred siting in Moss Vale.

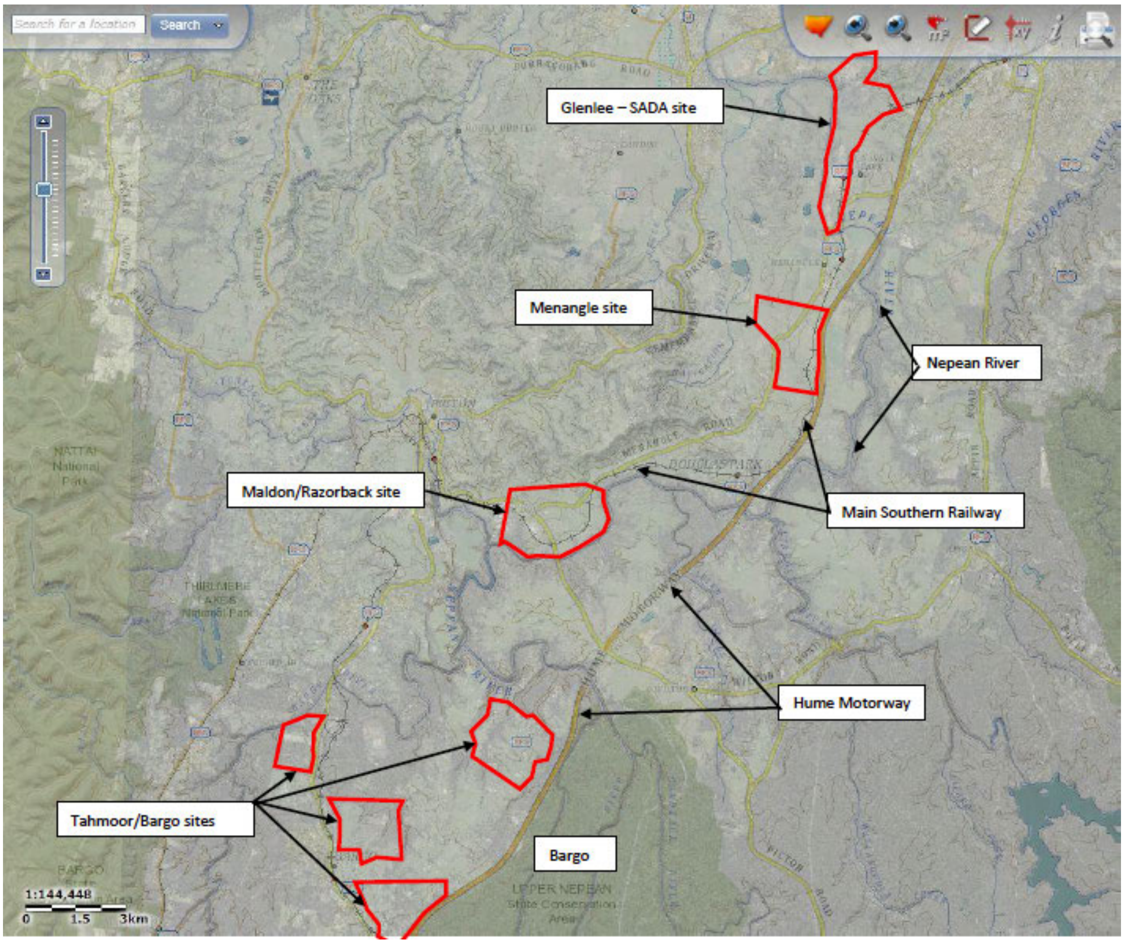
The *State Significant Development Guidelines- Preparing an Environmental Impact Statement* (Department of Planning, Infrastructure and Environment, July 2022) identifies that the consideration of alternatives (***emphasis*** added)

> "should also include an analysis of feasible alternatives considered having regard to the objectives of the development, including the consequences of not carrying out the development. The analysis of alternatives should explain how the project has ended up in its current form, summarising the key alternatives that have been considered and rejected (e.g. alternative ways of achieving the objectives of the development; ***and alternative sites***, designs, mitigation measures) ***and the reasons why they were rejected***. … If there are any detailed studies ***supporting the analysis of alternatives***, or if the related development is complex and requires a detailed explanation, then this material ***should be included in the appendices of the EIS*** or, where publicly available, referred to in the EIS."

The singular paragraph provided in the EIS to cover site selection fails to satisfy even the barest requirement of the guideline. There is no discernible consideration of the "do nothing" option.

The EIS has failed to consider valid alternatives, having proximity to both rail and highway access, on existing industrial lands, located away from residential areas such as:

- Glenlee
- Menangle
- Maldon/Razorback
- Tahmoor
- Bargo



Each of the above sites would offer suitable land scale, non-impacted by Aerotropolis and employment lands with synergies to local industry and substantively reduced impact and burden on local infrastructure.

However, the proponent has been unable to document any valid analysis or consideration of a site, or sites, leading it to a demonstrably logical identification and justification of the Moss Vale site as being the most suitable.

2.2.2 Treatment Train Options Assessment

No consideration, comparison or analysis of wastewater treatment options has been provided in the EIS.

In recent literature on the removal of microplastics from wastewater, a number of methods are identified – including physical, chemical and biological methods. These methods have varying removal efficiencies documented (ref Figure 2-1).

Figure 2-1 Identification and comparison of available microplastic treatment methods (Source: L. Dayal et al., 2024[10]).

Table 1
Comparison of various removal methods of microplastics.

Techniques	Microplastics removal efficacy (%)	Advantages	Disadvantages	References
Disc filtration	43.13–72.50	low energy use, accelerates the removal of microplastics from WWTPs	microplastics' fragment shape is difficult to effectively eliminate	Kwon et al. (2022)
Sand filtration	74–97	simple operation and low cost	efficacy to eliminate small particles is still not clear	Talvitie et al. (2017)
Membrane bioreactor technology	100	removing contaminants at varied concentrations while ensuring high-quality effluent and effective removal	limitations in aeration, membrane fouling, the requirement to supplement bacteria with nutritive ingredients, and expensive cost	Javier et al. (2020); Talvitie et al. (2017)
Photocatalytic degradation	nr*	eco-friendly, long-lasting	requires a lot of energy (ultraviolet light)	Uheida et al. (2021)
Magnetic separation		less waste sludge, high efficacy, high volume	large number of magnetic seeds required, separation of magnetic seeds and particles	Zhang et al. (2021a)
Adsorption removal		high reusability, affordable price, easy to use, and no harmful chemicals	low selectivity, prepared using an adsorbent	
Electrochemical oxidation		high efficiency, degrading a number of organic contaminants, not requiring the addition of chemical agents, and not producing sludge	high cost of electrodes	Chen et al. (2022)
Electrocoagulation	99	energy-efficient, economical, adaptable to automation, effective for removing small microplastics, reduced sludge, no need for chemical coagulants	replacement of the sacrificial anode and cathode passivation on a regular basis	Perren et al. (2018)
Coagulation	17–99	suitable for removing tiny microplastics, and low energy usage,l	Difficult to deal with multiple pollutants at once	Xu et al. (2021); Rajala et al. (2020)
Biochar filters	100	good adsorption capacity	Remove microplastics particle of micrometre size	Siipola et al. (2020)
Ozonation	89.9	low cost and high efficiency	Emission of hazardous substances from incomplete combustion is risky for the environment and people's health	Bui et al. (2020); Hidayaturrahman and Lee 2019
Bioinformatics	nr	environmentally friendly, Cost efficient	lack of experimental data and its validation	Ali et al. (2021); Anand et al. (2022)
Oil film separation	96	simple to use, affordable, and independent of density	hydrophobic surface required, organic contaminants entrainment	Zhang et al. (2021a)
Froth flotation	nr	quick operation, little space needs, adaptability of use, and moderate price	reagents for flotation, a hydrophobic surface, and entrainment of organic pollutants are all necessary	

nr*- not reported

Although DAF (as a froth flotation process) is identified as quick and moderately priced – this literature identifies that there are other alternative treatment options for microplastic removal which have superior removal efficiencies and hence may provide for better environmental and social outcomes. This includes, as identified in Section 1.1.1, consideration of a treatment train that employs a number of methods across physical, chemical and biological approaches – rather than a single methodology, particularly, a treatment train that includes substantive filtration processes such as reverse osmosis or ultrafiltration.

In the NHMRC *Australian Drinking Water Guidelines 6 2011* (updated 2022), it is recommended that preventative measures and management strategies should be developed on the basis of a system-specific hazard identification and risk assessment that adopts a multiple barrier principle. Measures should aim to prevent contamination in the catchment rather than relying on downstream control. The Guideline recommends (at Section A1.6), a documented process that involves:

- Identifying preventative measures for the hazard
- Determination of the residual risk
- Evaluation of alternatives and additional preventative measures
- Documentation of the preventative measures and strategies

[10] Dayal, L et al. "Recent advancement in microplastic removal process from wastewater – A critical review." The Journal of Hazardous Materials Advances vol. 16 (2024): 100460.

- Establishment of mechanisms to ensure cooperation and development of action plans with external agencies.

In the EIS's identification of the proposed DAF treatment for removal of microplastics, there has been no clear assessment of the residual risk to the environment.

No evaluation, analysis, or consideration has been given to alternatives or additional preventative measures – only a reliance on downstream control (being Council's WWTP). In establishing the proposed treatment methodology – there is no demonstrated consultation or coordination with external agencies. One key stakeholder (being Council) are opposed to the treatment train proposed and are seeking improved source control.

Based on the above review, the consideration of alternatives as presented in the development EIS is considered insufficient and seems to adopt a treatment process that represents the simplest and cheapest (to the Proponent) solution.

The minimum expectation should be the provision of an objective and balanced analysis and review of treatment technologies and options for treatment trains, including the "do nothing" option, that evaluates the nett environmental, social and economic advantages and disadvantages of each to support and justify a decision on the appropriate treatment methodology for the process, the site and the community.

It is difficult to understand how the proposed development can be accepted as being in the public interest or suitable to the site without a more robust consideration of alternative treatment train options.

2.3 Assessment of Noise

It is unclear whether the new access road to the proposed development has been assessed under the Roads Noise Policy or the Noise Policy for Industry. As the sole user/purpose of the road is to provide access to the site it should be assessed under the Noise Policy for Industry, as opposed to the Roads Noise Policy that is relevant to a genuine public thoroughfare.

2.4 Assessment of Impact on Air, Water and Biological Environments

As has been identified in some detail above, the EIS documentation fails to adequately identify, assess and evaluate the potential direct and indirect impacts of its operation in respect of generation and control of microplastics.

In Section 13 of the EIS, potential noise impacts and impacts of waste (including microplastics) on the environment are identified as being mitigated by ensuring roller doors are closed as much as possible and no other works would be undertaken outside.

Original correspondence from GHD (https://www.ipcn.nsw.gov.au/resources/pac/media/files/pac/transcripts-and-material/2024/moss-vale-plastics-recycling-facility/day-3-public-meeting-transcript-moss-vale-plastics-redacted.pdf, page 56) identified that roller doors are likely to be open for a total of 5 hours per day – which was based on an opening of 2 – 3 minutes per truck attending the facility.

This value has been revised by GHD in written correspondence to the IPC (November, 2024) as a result of 'more detailed analysis'. According to this correspondence, doors would now only be open for a total of 42 minutes per day – which is based on:

- the proposed roller doors opening and closing in 5 seconds
- a semi-trailer reversing completely into the building in 20 seconds
- a semi-trailer leaving the building in 10 seconds

Additionally, it assumes the truck itself provides a 'block' for airflow out of the building, and a negative air pressure system would further ensure wind would be drawn in, and not out.

The assessment of likely impacts is heavily reliant on the above optimal operating efficiency and without consideration of risks and outcome should this not be achieved. A precautionary rather than idealistic/subjective approach to mitigation and management of risk is required to sufficiently protect air, water and biological environments.

Independent verification of the procedural capability for the operation to perform in the manner described should be obtained. On its face, the only way to have reduced the timing for doors to be open is to reduce safety controls and/or increase the entry and exit speed of trucks.

Given the assumed load verification controls required before a truck can enter or leave the site, assuming trucks are not left idling during this process, and also assuming the doors are not left closed as the truck starts up and approaches a door (which presents a WHS / air quality issue internally), it is difficult to see how these revised times are achievable. A transparent and independent evaluation of this dramatic improvement is required.

2.5 Assessment of Risk – Particularly Fire Risk

The EIS fails to provide an adequate risk assessment for the development, considering likelihood and consequence. This is considered pertinent to a number of potential impacts related to the proposal – particularly fire.

The Planning Secretary's Environmental Assessment Requirements issued for the development (SSD-9409987,15/10/2020) identify that the EIS must include:

– *a risk assessment of the potential environmental impacts of the development, **identifying the key issues for further assessment***

The risk assessment provided in Appendix F has failed to adequately identify the accurate bushfire risk and the risk of microplastics generation and emission in waste streams.

Appendix E Community Engagement Session Minutes, identifies in a Thursday 29 July minutes table (at Action No. 14 – emphasis added):

> *"DG re-presented the slide which outlined the plastics recycling and reprocessing process and reiterated that the flaking stage would involve producing small pieces of plastic, approximately 5-10mm in size, **and not microplastics**. Each piece of equipment would have dust extraction systems and filter bags to collect any dust. **There would be virtually no opportunities for microplastics to escape from the buildings as part of the process**."*

Further (at Action 43 – emphasis added):

> *"It has been identified that the facility **would not produce any air emissions, microplastics** or VOCs."*

This appears to be contrary to the findings of various technical reports on plastics recycling facilities and their generation of microplastics in waste streams[11] (air, land and water). These aspects fail to be present in the Proponent's risk assessment in Appendix F and represent a failing to identify a key issue for further assessment.

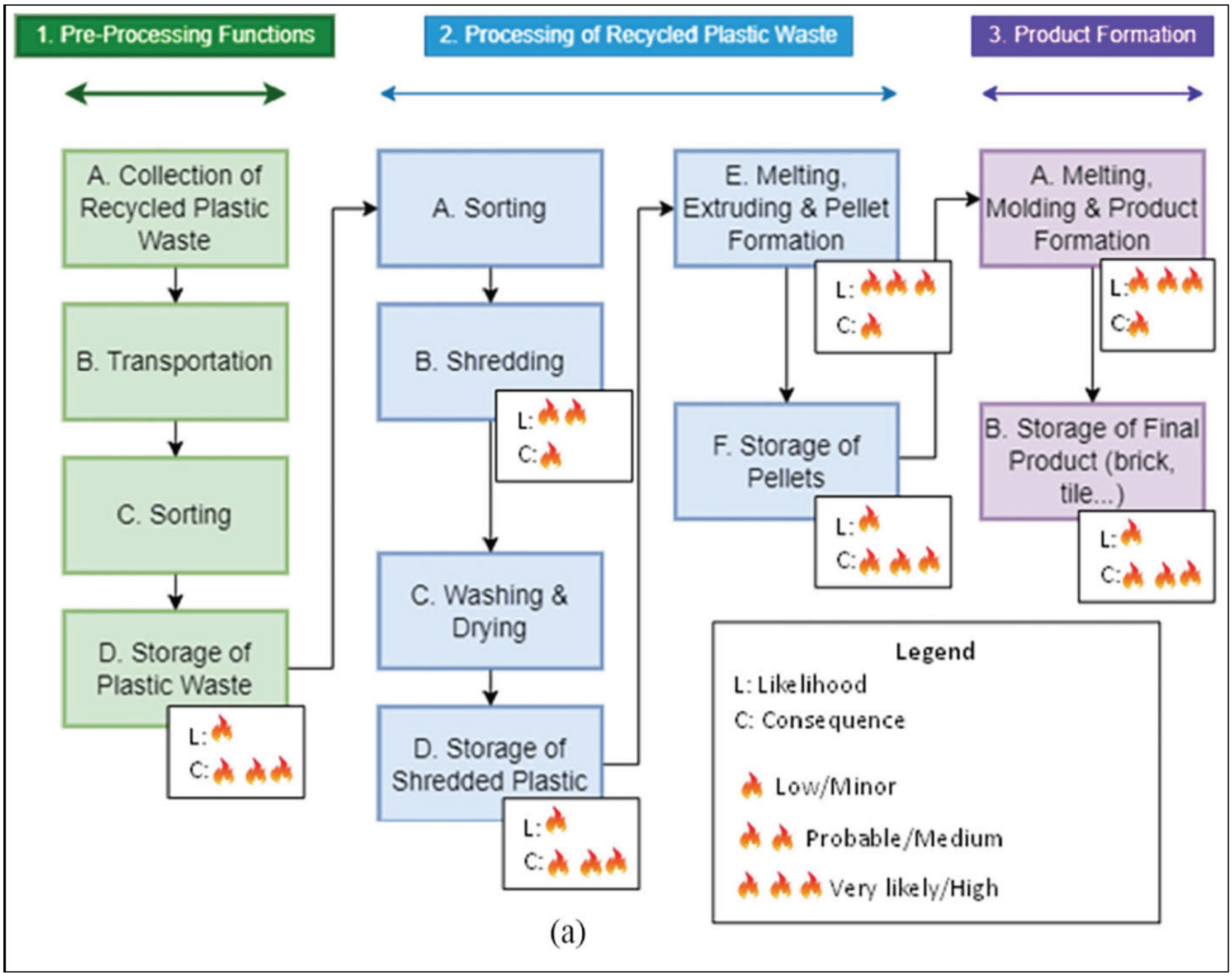
Fire risk associated from plastic recycling has numerous sources including:

- High Flammability: Plastics, particularly in pellet and flake form, are highly flammable. Once ignited, they burn intensely and release toxic gases.
- Dust Explosions: Plastic dust generated during the recycling process is combustible and poses a significant explosion risk if dispersed in the air and exposed to an ignition source.
- Static Electricity: Handling and transport of plastic pellets and flakes can generate static electricity, which can act as an ignition source, especially in dusty environments.
- Chemical Volatility: Refining processes involve the use of volatile chemicals and solvents, increasing fire risks in manufacturing facilities.
- Storage Conditions: Bulk storage of plastic pellets or flakes increases the risk of fire spreading rapidly due to the high surface area and ease of combustion of the materials.

[11] Singh, N., Walker, T.R. Plastic recycling: A panacea or environmental pollution problem. *npj Mater. Sustain.* **2**, 17 (2024)

These sources and conditions occur at numerous steps during all stages of plastic recycling and manufacturing (Figure 2-2). Fires associated with plastic recycling facilities are considered problematic and high risk due to their unpredictability, intensity and often long duration.

Figure 2-2 Plastic recycling process and likelihood and consequence of fire during the various steps (Source: Devine et al., 2023[12]).



The potential risk and consequence of fire within plastic recycling facilities has received increasing interest and review in literature in recent years. This may be attributed to the growing incidence of fire within facilities similar to that proposed by Plas Refine – with one recent media article (https://abcnews.go.com/Technology/plastic-building-recycling-centers-catching-fire/story?id=89125707) identifying that fires at waste and recycling facilities in the USA and Canada has increased from 343 reported fires in 2019 to 367 in 2021 (**Appendix C**).

Globally there have been hundreds of major incidents of fire associated with plastic recycling operations, including Formosa Plastics (USA) in 2019, X-Press Pearl Ship fire (Sri Lanka, 2021) and Shanghai Petrochemical Fire (China, 2022).

[12] Device, C et al. "Literature review and hazard identification relating to fire safety in commercial plastic recycling facilities." The Journal of Fire Sciences vol. 41(6) (2023): p 269 – 287.

The EIS does not identify or discuss any of the above, nor does it identify the mitigation measures that would be put in place to reduce the risk of these occurring.

The assessment also does not consider the wider potential implications as impacts that may result in the event of a fire at the Facility. These impacts would include:

- Environmental impacts:
  - Air quality impacts – release of toxins and particulate matter causing short- and long-term reduction in air quality.
  - Soil contamination – runoff from plastics and chemicals during firefighting may contaminate local soils.
  - Water (surface water and groundwater) contamination – dispersal of contaminates generated during a fire into downstream environments through migration via surface or groundwater.
  - Dispersion of microplastics – fire can cause plastics to break down into microplastics or break down microplastics into nanoplastics and disperse them into the environment via any of the above pathways.
- Social impacts:
  - Health implications on local community
  - Displacement – in the event of an evacuation from fire, or as a result of longer term and ongoing impacts
- Economic impacts:
  - Direct and indirect costs to the community associated with clean up, rebuilding, heath care and potential compensation.

The EIS notes, at Section 10.4.5 that the proposal would include 1,200 KL of water storage for firefighting purposes – which is noted as exceeding the AS 2419.1-2005 standard of 432 KL, and therefore removing any reliance on the potable water network in the event of a fire. The reliance in the application of this Australian Standard alone is problematic as:

- The Standard does not consider the nature of fire risk associated with plastic – which are known to be challenging to extinguish and can subsequently continue to burn for a prolonged period.
- The Standard uses floor area as the sole determinate of risk and does not consider volume.

It is therefore unclear whether sufficient water storage has been provided to manage a fire in the event that it occurs.

The absence of adequate consideration of fire risk is further exacerbated when considering the inadequate referencing of the site's status in terms of bushfire prone land mapping and consideration of updated mapping being likely to classify this area under Vegetation Category 3 - Grasslands.

In the absence of adequate consideration of the exposure risk of the site to bushfire or the risk of the facility itself being a source of an industrial fire combined with an absence of an objective evaluation of the consequential and cumulative risk of either, or both, of these events occurring, it is difficult to reasonably affirm that an adequate assessment of impact has been completed.

This in turn identifies the risk of the suite of identified mitigation and management strategies contained in the EIS are not adequate to mitigate, control or manage the full suite of impacts.

The inadequacy in demonstration of a reasonable and objective assessment of generation and emission of microplastics and fire risk within the EIS raises questions regarding the adequacy of the assessment as submitted.

2.6 Assessment of Direct and Indirect Impacts

The EIS focusses heavily on the direct impacts of the proposed development on the nominated site. It provides scant consideration of indirect and downstream impacts. In this instance 'downstream impacts' is meant in its literal sense of physically downstream via site water and wastewater discharges, as well as the downstream lifecycle of its product and waste stream.

Indirect and downstream impacts include product waste (particularly microplastics), energy generation, supply and consumption, infrastructure provision, operation and maintenance and greenhouse gas emissions. Their consideration should include each "*consequence which can reasonably be imputed as within the contemplation of the proponent of the [development], whether the consequences are within the control of the proponent or not*"[13].

It is considered that this should encompass consideration of cumulative indirect and downstream impacts, particularly noting the additional forecast trade waste loads to the MV WWTP and location of the proposed development within the Sydney Water drinking water catchment.

As the consent authority is required to assess direct and indirect impacts[14] the absence of identification and assessment of indirect impacts represents a deficiency in the current EIS documentation.

2.7 Assessment against ESD Principles

As has been identified in section 1.1.2 above, the EIS does not adequately demonstrate how the principles of ESD have been considered in the assessment or applied in the development. This deficiency is particularly noted in terms of:

- the identification of risks and potential impacts associated with microplastic wastes;
- consideration of the full plastics lifecycle and the deferral of landfilling rather than diverting waste from landfill;
- full valuation and nett environmental benefit analysis of the development for present and future generations encompassing resource demands, waste generation, exposure risk of waste materials, early decommissioning of the facility prior to the end of its operational life, and reliance on Local Council infrastructure to manage its waste streams (landfill and wastewater treatment).

[13] Minister for Environment and Heritage v Queensland Conservation Council (2004) 139 FCR 24 (Nathan Dam Case.

[14] *Gloucester Resources Limited v Minister for Planning* [2019] NSWLEC7.

3 Conclusion

It is considered that

- the inadequacies in the EIS assessment and consideration of impact management (including ESD principles)
- the absence of a valid, robust and meaningful consideration and analysis of alternatives (particularly siting and process treatment), including the "do nothing" option
- the absence of meaningful assessment of potential impacts associated with microplastics and identification of the associated regulatory void and its inherent risk in relation to the proposed development's waste streams
- the absence of a robust assessment of fire risk (both bushfire risk and process fire risk)
- the absence of full life cycle assessment and valuation of plastics recycling for the proposed development, including resource demands, short- and long-term waste streams and premature decommissioning costs, noting the intended 25-year operation
- the absence of meaningful and relevant consideration of the principles of ESD in the EIS and DPHI's Assessment report
- the uncertainties and inconsistencies contained within the conditions of consent

present an obstacle to any consent authority being able to reasonably and objectively demonstrate ability to satisfy its obligations under s4.15(1)(b) of the EP&A Act.

For this reason, it is considered that the IPC should refuse the application as proposed.

Additional reference information to support the IPC's consideration of the application is provided in the Appendices.

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Telstra Corporation Ltd v Hornsby Shire Council [2006] NSWLEC 133 (2006) 67 NSWLR 256

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Appendix A

Europe

- REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals): The EU's REACH regulation restricts intentionally added microplastics in products.
- Single-Use Plastics Directive (2019): Targets microplastics by restricting single-use plastics and requiring product design changes to reduce plastic waste, a primary source of secondary microplastics.
- Wastewater Treatment Standards: The Urban Wastewater Treatment Directive mandates high-efficiency wastewater treatment in all member states to capture microplastics.
- Plastic Packaging Levy: Implemented in 2021, this encourages recycling and reduction of plastic waste to reduce microplastic generation.

United States

- Microbead-Free Waters Act (2015): Bans plastic microbeads in rinse-off cosmetics and personal care products, does not address other forms of microplastics.
- State-Level Legislation: Some states (including California) have introduced regulations requiring microplastic monitoring in drinking water and examining tire particles as microplastic contributors.
- National Strategy for Plastic Pollution Reduction: Emerging federal efforts focus on broader plastic pollution but lack targeted microplastic-specific legislation.

Southeast Asia

- Plastic Pollution Pledges: Nations including Thailand, Indonesia, and Malaysia have committed to the ASEAN Framework of Action on Marine Debris, targeting plastic waste reduction by 2025, which includes reducing microplastics in waterways.
- National Waste Management Plans: Countries like Thailand and Indonesia focus on waste management to prevent plastic waste from entering oceans, indirectly reducing microplastic pollution.
- Southeast Asian policies often focus more on macroplastics and do not have strict, enforceable microplastic regulations.

Australia: New South Wales

- Microbeads Ban: Australia has a voluntary ban on microbeads in rinse-off products, following agreements among major retailers and manufacturers.
- NSW Plastic Reduction and Circular Economy Act 2021: Bans single-use plastics and supports a circular economy to minimize plastic pollution overall.
- NSW has monitoring programs to study microplastic levels in marine and urban waterways.
- National Approach: Australia has recently been working on guidelines and extended producer responsibility (EPR) schemes, aiming to phase out problematic plastics by 2025.

Australian Microbeads Ban

- **Overview**: Australia's microbeads ban is voluntary, focusing on phasing out plastic microbeads in rinse-off cosmetics, personal care, and cleaning products. This ban targets microbeads due to their significant contribution to marine pollution, their inability to biodegrade and persistence in the environment.
- Agencies Involved:
  - **Department of Climate Change, Energy, Environment and Water (DCCEEW):** DCCEEW has led efforts to negotiate the voluntary phase-out with major retailers and manufacturers.
  - **Australian Industrial Chemicals Introduction Scheme (AICIS)**: Provides guidelines for chemicals in products, including restrictions on microbeads.
  - **Australian Packaging Covenant Organisation (APCO)**: Involved in promoting industry commitments to the voluntary ban, supporting a transition to microbead-free alternatives.
- Recent Publications and Progress:
  - **2021 DCCEEW (then DAWE) Report**: A progress report confirmed a 99% reduction in the use of microbeads across targeted products. The voluntary phase-out has been largely successful, though DCCEEW continues monitoring compliance.
  - **Australia's National Waste Policy Action Plan (2020)**: This plan emphasizes the broader goal of reducing plastic pollution and indirectly supports the ban by promoting a circular economy and sustainable product design.

NSW Microplastics Monitoring Program

- **Overview**: The NSW microplastics monitoring program assesses microplastic pollution in marine, urban waterways, and coastal areas. It aims to understand the scale and sources of microplastic pollution in NSW and provide data for future regulatory and management decisions.
- **Agencies Involved**:
  - **NSW DCCEEW**: Leads the program, focusing on assessing pollution levels and sources.
  - **EPA (Environment Protection Authority)**: Works with NSW DCCEEW to implement environmental protection measures and monitors compliance with pollution regulations.
  - **University Collaborations**: Collaborations with research institutions, such as the University of New South Wales (UNSW) and Macquarie University, contribute to expertise and conduct field studies on microplastic levels and impacts.
- Recent Publications and Research:

- **NSW Marine Estate Management Authority Report (2020)**: This report provided a baseline assessment of microplastic pollution levels, particularly in estuarine and marine environments, highlighting high levels in urban waterways.
- **Recent UNSW Study on Microplastic Sources (2023)**: Identified significant sources of microplastic pollution in NSW's rivers, with particular emphasis on urban stormwater systems as a primary pathway.
- **EPA Annual Environmental Monitoring Reports**: These include data on plastic pollution, track changes over time, and assess the effectiveness of policy interventions.

World Health Organization (WHO)

- Microplastics in Drinking Water (2019 Report): Assessed the potential human health risks of microplastics in drinking water. The findings indicated that microplastics are present in drinking water globally but did not conclude that they pose an immediate health risk based on current evidence. WHO called for more research on potential impacts, especially focusing on particle toxicity, chemical additives, and microorganisms attached to microplastics.
- Research Recommendations: WHO emphasized the need for standardization in monitoring microplastics in water and called for further studies to clarify health effects, especially regarding exposure levels and particle size thresholds that might be harmful.

United Nations (UN)

UN Environment Programme (UNEP) Reports:

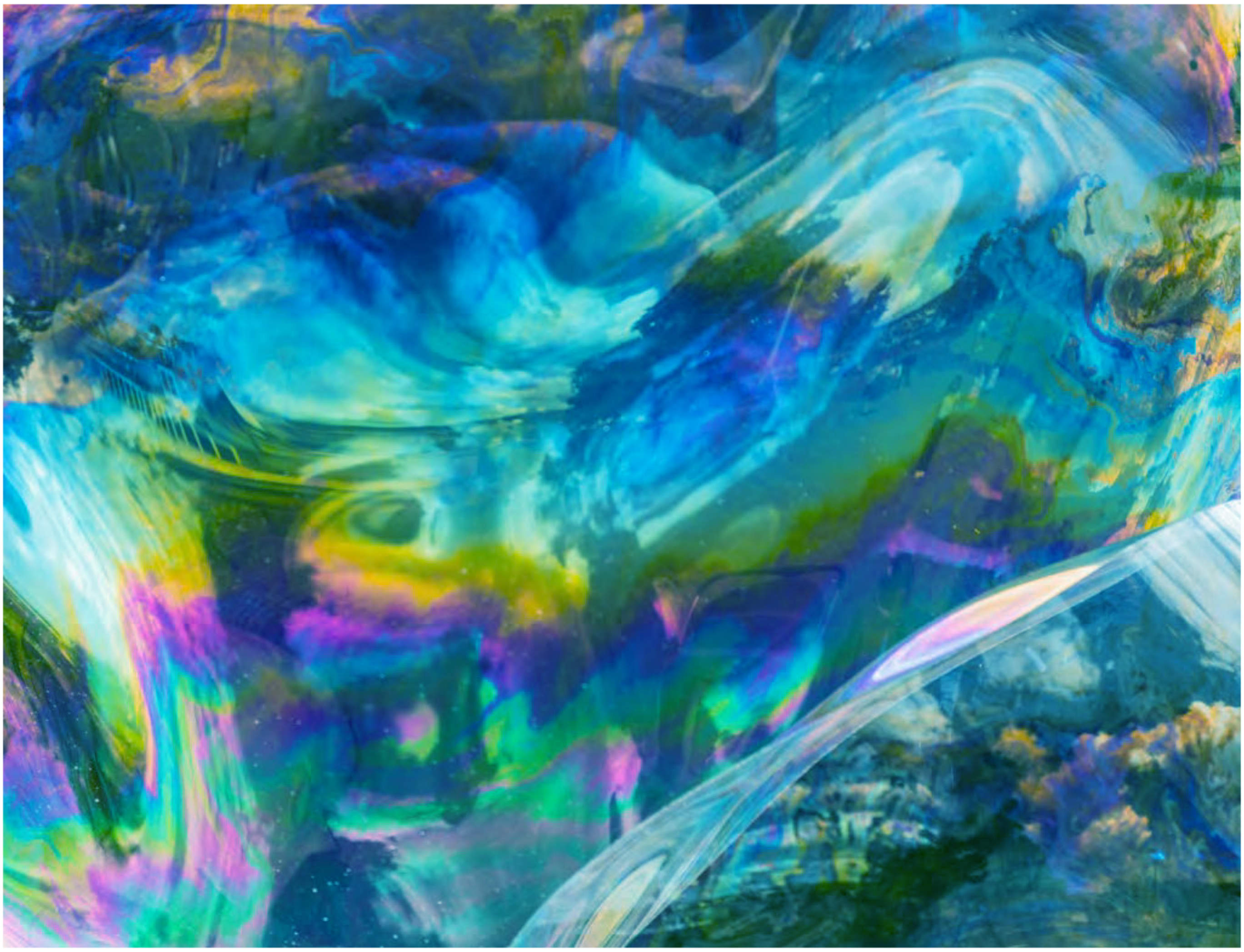
- Marine Litter and Microplastics (2018): UNEP published comprehensive guidelines on marine litter and microplastics, including recommendations for policies to reduce plastic pollution. This report advocates for circular economy principles, better waste management, and public awareness initiatives.
- Plastic Waste Partnerships and Campaigns: UNEP works with the Global Partnership on Marine Litter (GPML) to develop tools, guidelines, and collaborative projects to address microplastic pollution.
- Basel Convention Amendments (2019): Under UNEP's Basel Convention, amendments were introduced to control transboundary movements of plastic waste, encouraging proper management and reducing pollution sources for both macroplastics and microplastics.
- UN Sustainable Development Goals (SDGs): SDG 14 (Life Below Water) aims to reduce marine pollution by 2025, with microplastics as a focal area for policy development, research, and cleanup efforts.

International Union for Conservation of Nature (IUCN)

- Primary Microplastics in the Oceans Report (2017): Highlighted the major sources of primary microplastics entering the oceans, such as synthetic textiles, tire abrasion, and plastic packaging. The report has raised awareness on preventative measures, advocating for industry reforms to reduce microplastic shedding and encouraging improved wastewater treatment.
- Policy and Best Practices Guidance: IUCN collaborates with governments and organizations to promote policies on sustainable product design, source reduction, and waste management practices that help control microplastic generation.
- Marine Litter Toolkit: IUCN has developed a toolkit with best practices for reducing plastic pollution and addressing microplastic sources.

An Assessment Report on Issues of Concern: Chemicals and Waste Issues Posing Risks to Human Health and the Environment

September 2020



limitations in terms of what they can address: while efforts have been considerable, for example, in developing guidance and tools for testing, assessment, and identification of EDCs, a limited number of chemicals have been tested, identified, and regulated as EDCs in this arena.

An overarching challenge (as well as an opportunity) is how to communicate and scale up existing instruments and lessons learned in one region or sector to others, particularly for developing and transition countries. Detailed challenges and opportunities for individual issues are summarized below.

CiP	**(1)** Foster communication of chemicals present in products throughout the supply chain, versus the current common practice of communicating what should not be present. **(2)** Extend CiP communication to actors outside supply chains, e.g., by exploring instruments such as fiscal policies, extended producer responsibility, corporate sustainability reporting, and new public-private partnerships. **(3)** Ensure CiP information is relevant, accurate, current and accessible through strong regulatory and voluntary actions on effective monitoring and enforcement.
EDCs	**(1)** Regularly synthesize and disseminate relevant scientific evidence in a policy-ready format to bring governments and stakeholders worldwide to the same level of awareness and knowledge. **(2)** Strengthen dialogues and concerted actions at all levels to enable an effective and efficient way forward, including advancement and implementation of, for example, standard data requirements and testing methods, mutual acceptance of data and existing assessments, joint assessments and joint strategies for addressing EDCs.
EPPPs	**(1)** Expand the current scope under SAICM to encompass all pharmaceutical pollutants, including those that may not be long-lasting but may still accumulate in the environment due to continuous use and releases, and those that may lead to outcomes that are not readily reversible, such as antimicrobial resistance. **(2)** Step up global efforts to prevent pharmaceutical pollutants from entering waste streams, including strengthened engagement with pharmaceutical manufacturers, and filling in knowledge gaps of existing pharmaceuticals.
HSLEEP	**(1)** Address the early life-cycle stages of EEP, e.g., by taking proactive approaches such as adopting applicable fiscal policies and design guidelines to foster development of EEP made with minimal use of hazardous substances and by green manufacturing processes. **(2)** Properly address the situation of informal workers who handle EEP waste through improved understanding of their role and impacts on their health, best practices, and other conditions.
HHPs	**(1)** Address the current ambiguity of the criteria for identifying HHPs. **(2)** Strengthen international support for developing and transition countries, possibly through legally binding instruments and partnerships, including building up resources and capacities to establish and enforce national pesticide legislation, combatting illegal trafficking of illicit pesticides, and treatment of existing stockpiles.
Lead in paint	Continue global efforts in phasing out lead paints, including upscaling technical assistance in establishing legal limits, evaluation and improvement of the effectiveness of control measures, addressing lead pigments trade, fostering effective monitoring and enforcement, and exploring novel approaches to voluntary actions, while taking into account the specific circumstances and conditions in developing and transition countries.
Nanomaterials	**(1)** Establish regulatory data requirements on nanomaterials around the world, taking into account their properties and life cycles, to inform future hazard and risk assessments of them. **(2)** Strengthen dialogues and concerted actions at the international level to work towards common definitions and grouping strategies for nanomaterials.
PFASs	**(1)** Accelerate the global phase-out of those PFASs listed under the Stockholm Convention on Persistent Organic Pollutants. **(2)** Explore novel approaches to managing PFASs (e.g. grouping by similarities, the “essential use” concept in the Montreal Protocol). **(3)** Foster regular information exchange and joint efforts to accelerate actions on PFASs that are not listed under the Stockholm Convention, including transition to safer alternatives.

The issues identified by GCO-II warrant urgent international concerted actions

GCO-II identified 11 chemicals or groups of chemicals where emerging evidence indicates a risk. Environmental and human health effects are not a part of the assessment in this report; however, as noted in the report, a compilation of existing assessments by national governments and intergovernmental institutions confirms their possible significant adverse effects on the environment and humans. In addition, the assessment of current exposure to these substances, as well as existing instruments and actions, suggests pressing needs for international concerted action for all of them.

	Persistence in the environment?	Long-range transport potential?	Global prevalence of current exposure (and trends)?	Major sources being addressed globally?
Arsenic	✓	✓ (emissions from high-temperature processes)	✓	✗
Bisphenol A	✗	✗	✓ (↗ in adults)	✗
Cadmium	✓	✓ (emissions from high-temperature processes)	✓ (↘ in some regions, ↗ in others)	✗
Glyphosate	✓ (up to months to years in soil & sea water)	✓ (land-to-sea transport)	✓	✗
Lead	✓	✓ (emissions from high-temperature processes)	✓ (↗ as shown by global burden of disease data)	✗
Microplastics	✓	✓	✓	✗
Neonicotinoids	✓ (up to months to years in soil & sediment)	✗	✓	✗
Organotins	✓	✓ (some organotins)	✓	✗
Phthalates	✗	✗	✓	✗
PAHs	✓	✓	✓	✗
Triclosan	✗	✗	✓	✗

Overall, limited attention has been paid or actions taken for these issues, with uneven progress across countries and regions, although as with the issues of concern under SAICM, many of the issues identified by GCO-II have long been recognised (for over a century for lead, for example). Also, when instruments are established and actions taken, their scopes often are not comprehensive; for example, major sources of a substance may not

SYNTHESIS

UN environment programme | 50 1972-2022

FROM POLLUTION TO SOLUTION

A GLOBAL ASSESSMENT OF MARINE LITTER AND PLASTIC POLLUTION

For the rationale and background of this assessment, see Annex 1.

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KEY FINDINGS

1 The amount of marine litter and plastic pollution has been growing rapidly. Emissions of plastic waste into aquatic ecosystems are projected to nearly triple by 2040 without meaningful action.

The scale and rapidly increasing volume of marine litter and plastic pollution are putting the health of all the world's oceans and seas at risk. Plastics, including microplastics, are now ubiquitous. They are a marker of the Anthropocene, the current geological era, and are becoming part of the Earth's fossil record. Plastics have given their name to a new marine microbial habitat, the "plastisphere".

Despite current initiatives and efforts, the amount of plastics in the oceans has been estimated to be around 75-199 million tons. Estimates of annual global emissions from land-based sources vary according to the approaches used. Under a business-as-usual scenario and in the absence of necessary interventions, the amount of plastic waste entering aquatic ecosystems could nearly triple from some 9-14 million tons per year in 2016 to a projected 23-37 million tons per year by 2040. Using another approach, the amount is projected to approximately double from an estimated 19-23 million tons per year in 2016 to around 53 million tons per year by 2030.

2 Marine litter and plastics present a serious threat to all marine life, while also influencing the climate.

Plastics are the largest, most harmful and most persistent fraction of marine litter, accounting for at least 85 per cent of total marine waste. They cause lethal and sub-lethal effects in whales, seals, turtles, birds and fish as well as invertebrates such as bivalves, plankton, worms and corals. Their effects include entanglement, starvation, drowning, laceration of internal tissues, smothering and deprivation of oxygen and light, physiological stress, and toxicological harm.

Plastics can also alter global carbon cycling through their effect on plankton and primary production in marine, freshwater and terrestrial systems. Marine ecosystems, especially mangroves, seagrasses, corals and salt marshes, play a major role in sequestering carbon. The more damage we do to oceans and coastal areas, the harder it is for these ecosystems to both offset and remain resilient to climate change.

When plastics break down in the marine environment, they transfer microplastics, synthetic and cellulosic microfibres, toxic chemicals, metals and micropollutants into waters and sediments and eventually into marine food chains.

Microplastics act as vectors for pathogenic organisms harmful to humans, fish and aquaculture stocks. When microplastics are ingested, they can cause changes in gene and protein expression, inflammation, disruption of feeding behaviour, decreases in growth, changes in brain development, and reduced filtration and respiration rates. They can alter the reproductive success and survival of marine organisms and compromise the ability of keystone species and ecological "engineers" to build reefs or bioturbated sediments.

3 Human health and well-being are at risk

Risks to human health and well-being arise from the open burning of plastic waste, ingestion of seafood contaminated with plastics, exposure to pathogenic bacteria transported on plastics, and leaching out of substances of concern to coastal waters. The release of chemicals associated with plastics through leaching into the marine environment is receiving increasing attention, as some of these chemicals are substances of concern or have endocrine disrupting properties.

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Microplastics can enter the human body through inhalation and absorption via the skin and accumulate in organs including the placenta. Human uptake of microplastics via seafood is likely to pose serious threats to coastal and indigenous communities where marine species are the main source of food. The links between exposure to chemicals associated with plastics in the marine environment and human health are unclear. However, some of these chemicals are associated with serious health impacts, especially in women.

Marine plastics have a widespread effect on society and human well-being. They may deter people from visiting beaches and shorelines and enjoying the benefits of physical activity, social interaction, and general improvement of both physical and mental health. Mental health may be affected by the knowledge that charismatic marine animals such as sea turtles, whales, dolphins and many seabirds are at risk. These animals have cultural importance for some communities. Images and descriptions of whales and seabirds with their stomachs full of plastic fragments, which are prevalent in mainstream media, can provoke strong emotional impacts.

4 There are hidden costs for the global economy.

Marine litter and plastic pollution present serious threats to the livelihoods of coastal communities as well as to shipping and port operations. The economic costs of marine plastic pollution with respect to its impacts on tourism, fisheries and aquaculture, together with other costs such as those of clean-ups, are estimated to have been at least United States dollars (US$) 6-19 billion globally in 2018. It is projected that by 2040 plastic leakage into the oceans could represent a US$ 100 billion annual financial risk for businesses if governments require them to cover waste management costs at expected volumes and recyclability. By comparison, the global plastic market in 2020 has been estimated at around US$ 580 billion while the monetary value of losses of marine natural capital is estimated to be as high as US$ 2,500 billion per year.

5 Marine litter and plastics are threat multipliers.

The multiple and cascading risks posed by marine litter and plastics make them threat multipliers. They can act together with other stressors, such as climate change and overexploitation of marine resources, to cause far greater damage than if they occurred in isolation. Habitat alterations in key coastal ecosystems caused by the direct impacts of marine litter and plastics affect local food production and damage coastal structures, leading to wide-reaching and unpredictable consequences including loss of resilience to extreme events and climate change in coastal communities. The risks of marine litter and plastics therefore need to be assessed across the wider cumulative risks.

6 The main sources of marine litter and plastic pollution are land-based.

Approximately 7,000 million of the estimated 9,200 million tons of cumulative plastic production between 1950 and 2017 became plastic waste, three-quarters of which was discarded and placed in landfills, became part of uncontrolled and mismanaged waste streams, or was dumped or abandoned in the environment, including at sea. Microplastics can enter the oceans via the breakdown of larger plastic items, leachates from landfill sites, sludge from wastewater treatment systems, airborne particles (e.g. from wear and tear on tyres and other items containing plastic), run-off from agriculture, shipbreaking, and accidental cargo losses at sea. Extreme events such as floods, storms and tsunamis can deliver significant volumes of debris into the oceans from coastal areas and accumulations of litter on riverbanks, along shorelines and in estuaries. With global cumulative plastic production between 1950 and 2050 predicted to reach 34,000 million tons, it is urgent to reduce global plastic production and flows of plastic waste into the environment.

7 The movement and accumulation of marine litter and plastics occur over decades.

The movement of marine litter and plastics on- and offshore is controlled by ocean tides, currents, waves and winds, with floating plastics accumulating in the ocean gyres and sinking items concentrating in the deep sea, river deltas, mud belts and mangroves. There can be significant time intervals between losses on land and accumulation in offshore waters and deep-sea sediments. More than half the plastics found floating in some gyres were produced in the 1990s and earlier.

There are now a growing number of hotspots in which there is potential for long-term, large-scale risks to ecosystem functioning and human health. Major sources include the Mediterranean Sea, where large volumes of marine litter and plastic accumulate due its enclosed nature, presenting risks to millions of people; the Arctic Ocean because of potential damage to its pristine nature and harm to indigenous peoples and iconic species through ingestion of plastics in marine food chains; and the East and Southeast Asian region, where there are significant volumes of uncontrolled waste in proximity to very large human populations with a high dependency on the oceans.

8 Technological advances and the growth of citizen science activities are improving detection of marine litter and plastic pollution, but consistency of measurements remains a challenge.

There have been significant improvements in regard to effective and affordable global observational and surveying systems, as well as the protocols for detecting and quantifying litter and microplastics in physical and biotic samples. However, concerns remain among scientists about sampling biases in the determination of the absolute volumes of microplastics found in different habitats owing to high variability in physical and chemical characteristics and the need for greater consistency among different sampling and observation platforms and

instruments. There are currently 15 major operational monitoring programmes linked to marine litter action co-ordination, data collection frameworks, and large-scale data repository and portal initiatives, but the data and information from them are largely unconnected. Alongside these programmes are indicator processes and baseline data collection activities, supported by a growing number of networks, citizen science projects and participatory processes worldwide.

9 Plastic recycling rates are less than 10 per cent and plastics-related greenhouse gas emissions are significant, but some solutions are emerging.

During the past four decades global plastic production has more than quadrupled, with the global plastic market valued at around US$ 580 billion in 2020. At the same time, the estimated global cost of municipal solid waste management is set to increase from US$ 38 billion in 2019 to US$ 61 billion in 2040 under a business-as-usual scenario. The level of greenhouse gas emissions associated with the production, use and disposal of conventional fossil fuel-based plastics is forecast to grow to approximately 2.1 gigatons of carbon dioxide equivalent ($GtCO_2e$) by 2040, or 19 per cent of the global carbon budget. Using another approach, GHG emissions from plastics in 2015 were estimated to be 1.7 $GtCO_2e$ and projected to increase to approximately 6.5 $GtCO_2e$ by 2050, or 15 per cent of the global carbon budget.

A major problem is the low recycling rate of plastics, which is currently less than 10 per cent. Millions of tons of plastic waste are lost to the environment, or sometimes shipped thousands of kilometres to destinations where it is generally burned or dumped. The estimated annual loss in the value of plastic packaging waste during sorting and processing alone is US$ 80-120 billion. Plastics labelled as biodegradable present another problem, as they may take a number of years to degrade in the oceans and, as litter, can present the same risks as conventional plastics to individuals, biodiversity and ecosystem functioning.

A single-solution strategy will be inadequate to reduce the amount of plastics entering the oceans. Multiple synergistic system interventions are needed upstream and downstream of plastic production and use. Such interventions are already emerging. They include circularity policies, phasing out of unnecessary, avoidable and problematic products and polymers, fiscal instruments such as taxes, fees and charges, deposit-refund schemes, extended producer responsibility schemes, tradeable permits, removal of harmful subsidies, green chemistry innovations for safer alternative polymers and additives, initiatives to change consumer attitudes, and "closing the tap" in regard to virgin plastic production through new service models and ecodesign for product reuse.

10 Progress is being made at all levels, with a potential global instrument in sight.

A growing number of global, regional and national activities are helping to mobilize the global community in order to bring an end to marine litter and plastic pollution.

Cities, municipalities and large firms have been reducing waste flows to landfills; regulatory processes are expanding, driven by growing public pressure; and there has been an upsurge in local activism and local government actions including kerbside collections, plastics recycling and community clean-ups. However, the current situation is a mixture of widely varying business practices and national regulatory and voluntary arrangements.

There are already some international commitments to reduce marine litter and plastic pollution, especially from land-based sources, as well as several applicable international agreements and soft law instruments relating to trade in plastics or to reducing impacts on marine life. However, none of the international policies agreed since 2000 includes a global, binding, specific and measurable target limiting plastic pollution. This has led many governments, as well as business and civil society, to call for a global instrument on marine litter and plastic pollution.

Dietary and inhalation exposure to **nano- and microplastic particles** and potential implications for human health

World Health Organization

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CONTENTS

TABLES

BOXES

Microplastics in drinking-water

Key messages

- Microplastics are ubiquitous in the environment and have been detected in a broad range of concentrations in marine water, wastewater, fresh water, food, air and drinking-water, both bottled and tap water. The data on the occurrence of microplastics in drinking-water are limited at present, with few fully reliable studies using different methods and tools to sample and analyse microplastic particles.
- The potential hazards associated with microplastics come in three forms: physical particles, chemicals and microbial pathogens as part of biofilms. Based on the limited evidence available, chemicals and biofilms associated with microplastics in drinking-water pose a low concern for human health. Although there is insufficient information to draw firm conclusions on the toxicity related to the physical hazard of plastic particles, particularly for the nano size particles, no reliable information suggests it is a concern.
- Limited evidence suggests that key sources of microplastic pollution in fresh water sources are terrestrial run-off and wastewater effluent. However, optimized wastewater (and drinking-water) treatment can effectively remove most microplastics from the effluent. For the significant proportion of the population that is not covered by adequate sewage treatment, microbial pathogens and other chemicals will be a greater human health concern than microplastics.

Recommendations

- **Water suppliers and regulators** should continue to prioritize removing microbial pathogens and chemicals from drinking-water that are known significant risks to human health. As part of water safety planning, water suppliers should ensure that control measures are effective, including optimizing water treatment processes for particle removal and microbial safety, which will incidentally improve the removal of microplastic particles. Routine monitoring of microplastics in drinking-water is not necessary at this time.
- To better assess the human health risks and inform management actions, **researchers** should undertake targeted, well-designed and quality-controlled investigative studies to better understand the occurrence of microplastics in the water cycle and in drinking-water throughout the water supply chain, the sources of microplastic pollution and the uptake, fate and health effects of microplastics under relevant exposure scenarios.
- Irrespective of any human health risks posed by exposure to microplastics in drinking-water, measures should be taken by **policy makers and the public** to better manage plastics and reduce the use of plastics where possible, to minimize plastics released into the environment because these actions can confer other benefits to the environment and human well-being.

Key questions and answers

What are microplastics?

As a category, microplastics encompass a wide range of materials composed of different substances, with different densities, chemical compositions, shapes and sizes. There is no scientifically-agreed definition of microplastics, although they are frequently defined as plastic particles <5 mm in length. However, this is a rather arbitrary definition and is of limited value in the context of drinking-water since particles at the upper end of the size range are unlikely to be found in treated drinking-water. A subset of microplastics <1 µm in length are often referred to as nanoplastics.

How do microplastics get into drinking-water?

Microplastics may enter drinking-water sources in a number of ways: from surface run-off (e.g. after a rain event), to wastewater effluent (both treated and untreated), combined sewer overflows, industrial effluent, degraded plastic waste and atmospheric deposition. Surface run-off and wastewater effluent are recognized as the two main sources, but better data are required to quantify the sources and associate them with more specific plastic waste streams. Plastic bottles and caps that are used in bottled water may also be sources of microplastics in drinking-water.

How much microplastic has been found in drinking-water and drinking-water sources?

In freshwater studies, reported microplastic particle counts ranged from around 0 to 1000 particles/L. Only nine studies were identified that measured microplastics in drinking-water; these studies reported particle counts in individual samples from 0 to 10 000 particles/L and mean values from 10^{-3} to 1000 particles/L. A comparison of the data between fresh water and drinking-water studies should not be made because in most cases freshwater studies targeted larger particles, using filter sizes that were an order of magnitude larger than those used in drinking-water studies.

What kinds of microplastics are being found?

In fresh water a wide variety of particle shapes have been found while the polymers most frequently detected roughly correlates with plastic production volumes. In drinking-water, fragments and fibres were the predominant particle shapes and polyethylene terephthalate and polypropylene were the polymers most detected.

Can these studies be trusted?

A WHO-commissioned study concluded that most of these studies are not fully reliable because their methods lacked sufficient quality control. Results should therefore be interpreted with caution. The quality control areas requiring the most improvement included sample treatment, polymer identification, laboratory preparation, clean air conditions and positive controls. For example, in two drinking-water studies and for a subset of smaller particles in a third study, no spectroscopic analysis was conducted to confirm that the particles identified were plastic. Four of the 52 studies that scored highest for quality were published in 2017 and 2018, indicating some improvements in quality control.

What are the potential threats posed by microplastics in drinking-water?

The potential hazards associated with microplastics come in three forms: physical particles, chemicals and microbial pathogens that are part of biofilms. Particles may cause impacts in the body, depending on a range of physicochemical properties of the particle, including size, surface area and shape. However, the fate, transport and health impacts of microplastics following ingestion are not well studied, with no human studies on ingested microplastics. Although plastic polymers are generally considered to be of low toxicity, plastics and microplastics can contain unbound monomers and additives. Hydrophobic chemicals in the environment, including persistent organic pollutants, may also sorb to the plastic particle. Biofilms in drinking-water are formed when microorganisms grow on drinking-water distribution systems and other surfaces. Most microorganisms that are part of biofilms are non-pathogenic. However, some biofilms can include pathogens such as *Pseudomonas aeruginosa*, *Legionella* spp., non-tuberculosis *Mycobacterium* spp. and *Naegleria fowleri*.

The health risk from microplastics in drinking-water is a function of both hazard (potential to cause adverse effects) and exposure (dose). The same substance can have different effects at different doses, which depends on how much of the substance a person is exposed to and may also depend on the route by which the exposure occurs, e.g. ingestion, inhalation or injection. The risks associated with each hazard class are further described below.

What is the human health risk of ingesting microplastic particles through drinking-water?

Although there is insufficient information to draw firm conclusions on the toxicity of plastic particles and particularly the nano size particles, no reliable information suggests it is a concern. Studies on absorption indicate that microplastics >150 µm are likely to be excreted directly through faeces. Uptake of smaller particles is expected to be limited, although absorption and distribution of very small microplastic particles including nanoplastics may be higher. Toxicology studies in rats and mice reported some impacts including inflammation of the liver. However, these few studies are of questionable reliability and relevance, with findings reported at very high exposures that would not occur in drinking-water.

What is the human health risk from chemicals associated with microplastics in drinking-water?

Risk assessments have been conducted for many chemicals to determine the level at which no or limited adverse effects should occur (toxicological point of departure, POD). To assess health risks of chemicals associated with microplastics, a margin of exposure (MOE) assessment was conducted for the chemicals that have been detected in microplastics, are of toxicological concern and have adequate or accepted toxicological PODs. Since there are several orders of magnitude difference between estimated intakes from a very conservative exposure scenario and the PODs, chemicals associated with microplastics in drinking-water are a low concern.

What is the human health risk associated with biofilms that attach to microplastics in drinking-water?

Biofilms associated with microplastics are considered a low health concern considering the relative concentration of microplastics compared to other particles that pathogens can adhere to in fresh water. For microplastics that are not removed during drinking-water treatment, the relative significance of microplastic-associated biofilms is still likely negligible due to the larger mass of drinking-water distribution systems and their subsequent ability to support more biofilms, compared to microplastics. Disinfection, including in distribution systems can inactivate pathogens and control their growth.

How do the risks from microplastics stack up against other potential risks to drinking-water?

Microbial pathogens represent the most significant public health threat in drinking-water. In 2016, 485 000 diarrhoeal related deaths were attributed to microbially-contaminated drinking-water (Prüss-Ustün, 2019) and it is estimated that 2 billion people are drinking faecally contaminated water (WHO, UNICEF, 2017).

A significant source of faecal contamination in drinking-water is inadequately or untreated wastewater. About 20% of wastewater collected in sewers does not undergo at least secondary treatment and an even higher proportion of people lack access to sewage connections or other appropriate systems for collecting and treating wastewater. Therefore, although wastewater effluent is recognized as a key source of microplastic pollution in freshwater, pathogens and other chemicals associated with the lack of effective sewage treatment are of greater concern. By addressing the bigger problem of exposure to faecally contaminated water, communities can simultaneously address the smaller concern related to microplastics.

How can microplastics be removed from drinking-water?

Wastewater and drinking-water treatment systems—where they exist and are optimized—are considered highly effective in removing particles of similar characteristics and sizes as microplastics. According to available data, wastewater treatment can effectively remove more than 90% of microplastics from wastewater with the highest removals from tertiary treatment such as filtration. Drinking-water treatment has proven effective in removing far more particles of smaller size and at far higher concentrations than those of microplastics. Conventional treatment, when optimized to produce treated water of low turbidity, can remove particles smaller than a micrometre. Advanced treatment can remove even smaller particle; for example, nanofiltration can remove particles >0.001 µm while ultrafiltration can remove particles >0.01 µm.

Based on the conclusions of the report, should any actions be taken to minimize microplastic pollution in drinking-water? If so, what actions should be taken?

Irrespective of any human health risks posed by microplastics in drinking-water, policy-makers and the public should take action to minimize plastics released into the environment, since these actions will confer multiple other benefits for the environment and human well-being. Actions could include reducing the use of plastics where possible, improving recycling programmes, reducing littering, improving circular solutions and decreasing industrial waste inputs into the environment. Care must be taken, however, to select mitigating actions that do not create new problems.

Based on the conclusions of the report, what actions should be taken by water suppliers and drinking-water regulators?

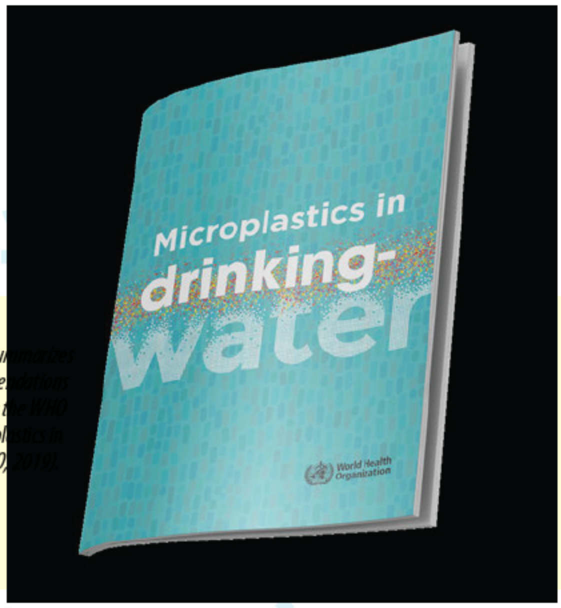
Water suppliers and regulators should continue to prioritize the removal of microorganisms and chemicals in drinking-water that pose a public health concern. As part of water safety planning, water suppliers should ensure that control measures are effective and should optimize water treatment processes for particle removal and microbial safety, which will incidentally improve the removal of microplastic particles. Routine monitoring of microplastics in drinking-water is not recommended at this time, as there is no evidence to indicate a human health concern.

What further research is needed?

A number of research gaps need to be filled to better assess the risk of microplastics in drinking-water and inform management actions. Targeted, well-designed and quality-controlled investigative studies should be carried out to better understand microplastics occurrence throughout the water supply chain, including the numbers, shapes, sizes, composition and sources of microplastics and to better characterize the effectiveness of water treatment. Research is also needed to understand the significance of treatment-related waste streams as contributors of microplastics to the environment. Quality-assured toxicological data are needed on the most common forms of plastic particles relevant for human health risk assessment. Further, a better understanding on the uptake and fate of microplastics and nanoplastics following ingestion is needed. Finally, given that humans can be exposed to microplastics through a variety of environmental media, including food and air, a better understanding of overall exposure to microplastics from the broader environment is needed.

Where will WHO direct its future research on the human-health effects of microplastics in the environment?

Given that humans can be exposed to microplastics through a variety of environmental media, WHO has initiated a broader assessment of microplastics in the environment. A future report will characterize the potential human health risks due to total microplastic exposure from the environment, including through food and air.



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This information sheet summarizes key findings, recommendations and conclusions from the WHO technical report, Microplastics in drinking-water (WHO, 2019).

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National Water Quality Management Strategy

Australian Drinking Water Guidelines 6
2011

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Appendix B

Effectiveness of Dissolved Air Flotation on Microplastics

Dissolved Air Flotation (DAF) systems are primarily designed for removing suspended solids, oils, and other contaminants from wastewater, often through the process of coagulation, flocculation, and flotation. The system works by injecting dissolved air into wastewater, causing fine bubbles to form and attach to suspended particles, making them buoyant so they can be removed from the water's surface.

Regarding microplastics, DAF systems have limited effectiveness compared to other methods designed specifically for filtering fine particulate matter like microplastics. Key factors that influence the performance of DAF systems in removing microplastics are:

Effectiveness of DAF Systems for Microplastics

1. Size and Nature of Microplastics:
   - Microplastics Size: Microplastics typically range in size from a few microns to several millimetres. DAF systems are more effective at removing larger particles or those that can form flocs when treated with coagulants. Microplastics, particularly those below 10 microns, may not readily form large enough flocs to float effectively.
   - Shape and Density: Microplastics vary in shape and density. Many are lightweight and hydrophobic (repelling water), meaning they may not easily attach to air bubbles in the DAF process. This reduces their removal efficiency, especially if the microplastics are very small or have a low density.
2. Coagulation and Flocculation:
   - DAF systems typically rely on the addition of coagulating agents to help larger particles clump together, forming flocs that can float to the surface. However, microplastics may not form effective flocs, particularly if they are of certain polymer types (e.g., polyethylene or polypropylene), which are less likely to aggregate without the presence of specific additives or chemicals.
3. Removal Efficiency:
   - Several studies suggest that DAF systems can remove a portion of microplastics, but their efficiency is lower compared to filtration or advanced treatment technologies like membrane filtration (e.g., microfiltration, ultrafiltration). For example, DAF systems are typically reported to remove between 10-60% of microplastics, depending on the size and nature of the microplastics and the specific setup of the system.
   - Enhanced Coagulation: In some instances, introducing specialized coagulants or flocculants tailored to microplastic particles can improve removal efficiency, but these treatments are not standard and require careful management to ensure optimal performance.

Alternatives and Complementary Methods

- Membrane Filtration: Advanced filtration methods, particularly microfiltration and ultrafiltration, are far more effective in removing microplastics. These systems can filter out particles as small as 0.1 microns, making them well-suited for capturing microplastics.

- Sand and Granular Media Filtration: This method can also effectively remove larger microplastics, but like DAF systems, it is not as efficient for very fine microplastics.
- Chemical Treatments: Some studies have explored the use of coagulants specifically designed for microplastics, which can aid in their aggregation and improve removal by flotation or sedimentation processes.

Summary

While DAF systems can remove some microplastics, their overall effectiveness is limited, especially for smaller, lighter microplastics. For higher removal efficiency, membrane filtration or other specialized technologies are more effective. However, DAF systems can still be a useful part of an integrated treatment approach for wastewater containing microplastics, especially when paired with other technologies like advanced coagulation or filtration systems.

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Recent advancement in microplastic removal process from wastewater - A critical review

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ABSTRACT

Microplastics, small sized plastic particles having size <5 mm are formed through primary process including production of beauty products, microbeads and microfibres as well as secondary process including mechanical weathering, friction, aberration and fragmentation of large plastics. The major sources of microplastics are land-based and ocean-based sources. Microplastic pollution is a serious concern due to the persistent, low biodegradability and bio-accumulative behaviour. Microplastics can bioaccumulate in the food chain and can cause ecological and human health risk. Hence, it is important to remove from the aquatic ecosystems. Microplastics are removed from aquatic systems and wastewater through a series of processes such as physical, chemical and biological treatments. In the present articles, >250 articles are reviewed to collect the information regarding the various physical, chemical and biological methods for the removal of microplastics. Also, the probable control strategies to combat with plastic pollution were assessed. It was concluded that recent water treatment methods are efficient in removing microplastic pollution. The efficiencies to remove microplastic from the water ranged between 74 %-99.2 %, 65 %-99.20 % and 77 %-100 % for physical, chemical and biological treatment methods, respectively. Among the three treatment methods, physical methods especially the filtration of water from biochar is the most efficient way (efficiency up to 100 %) to remove microplastics. It was also concluded that creating public awareness, promoting reusing, recycling and reducing, and application of bioplastics can control the production of microplastics from plastic wastes. This review will be useful to add current knowledge regarding the abatement of microplastic pollution, and finding novel solution to control microplastics. This review will also help the policymakers to implement most effective and cost-efficient method to remove microplastics, and to find out new methods to reduce, reuse and recycle plastic wastes.

1. Introduction

Modern technology has made plastics one of the most extensively used materials in recent times, and thus plastics are thought to be an indicator of the Anthropocene. The most severe fear of the worldwide environment is plastic pollution (Aragaw, 2020). The worldwide plastic output surged to >360 million tonnes in 2018 and is projected to get tripled by 2050. According to a report, Asia produces and consumes the most goods made up of plastic, while China accounting for this majority which is 32 % of the "white pollution" (Plastics Europe, 2020). Even though the World Health Organisation (WHO) has established strict guidelines for the environmental disposal of solid wastes, improper waste disposal in unlicensed dumps without segregation and inadequate infrastructure have made it more difficult to manage them. Plastic pollution is one of the major global concerns because it is directly connected with many of United Nation Sustainable Development Goals such as SDG 3 - Good health and well-being, SDG 6 - Clean water and sanitation, SDG 11- Sustainable cities and communities, SDG 12 - Responsible consumption and production, SDG 13 - Climate action, SDG 14 - Life below water and SDG 15 - Life on land. Plastic particles that are <5 mm in dimension are called as microplastics (Dayal et al. 2024). These microplastics are formed through primary processes i.e. cosmetics and beauty care products, microbeads, microfibres, etc. and secondary processes i.e. weathering, friction, aberration, and fragmentation of larger

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plastic wastes (Raj and Maiti, 2023) (Fig. 1). Almost 80 to 90 % of the microplastics found in waterbodies come from land-based sources (Karapanagioti, 2017; Kosore et al., 2018). These sources include plastic bottles, bags, toiletries, building supplies, and apparel. Plastic incinerator creates bottom ash, which is a terrestrial source of microplastics (Osman et al., 2023).

Oceanic-based sources, such as seashore tourism, industrial fishing, and sea boats, are responsible for 10–20 % of the microplastics released into the marine environment (Li, 2018). Microplastics are buoyant at various ocean layers and are commonly produced by lost or abandoned fishing equipment, such as nylon nets and plastic monofilament lines (Naji et al., 2017; Osman et al., 2023). Every year, around 600,000 tonnes of fishing gear are dumped into the ocean, and a major portion are contributed by commercial and military vessels and trash from ships (Good et al., 2010; Peng et al., 2018; Vaid et al., 2021). However, ocean-based sources make up a smaller portion of the microplastics pollution compared to land-based sources, they nonetheless have a sizable impact.

Microplastics are ubiquitously present in a broad range of shapes, polymers, sizes and concentration in marine and freshwater ecosystems, atmosphere, drinking water and food and affects every component of the ecosystem (Blackburn and Green 2022). Microplastic accumulation in plants are known to cause inhibition of shoot and root development, reduction in growth of plants and alteration in the nutrient uptake in plants (Kumari and Raj 2024). In aquatic animals, intake of microplastics causes kidney damage, gill inflammation, oxidative stress, glycogen depletion, cell necrosis, liver damage, inflammation in gastrointestinal tract and abnormalities in reproductive organs, etc. (Dayal et al. 2024). Human beings, the top consumer of any food chains are more vulnerable to microplastics due to ingestion of aquatic food. In human, microplastics are known to affect immune and stress responses and induce reproductive and developmental toxicity (Blackburn and Green 2022).

Numerous studies have illustrated the occurrence of the microplastics in water (Yuan et al., 2019), soil (Scheurer and Bigalke, 2018; Chia et al., 2022), and sediment (Vaid et al., 2021; Chauhan et al., 2021). Every year, tonnes of plastic trash is discarded into many surface water sources. Effluents from treatment plants are also the primary source of plastic. Water bodies receive either processed or untreated wastewater through various point and non-point sources, has the potential to be a source of microplastics. The larger size plastic particle (macro-plastic) can be removed via screening systems (pre-treatment) but the removal of small sized microplastic particles is quite challenging and requires a series of treatment processes. Some literature suggests various conventional, non-conventional and hybrid microplastic removal methods. Some research shows the probable effects of microplastics in living organisms and human beings.

Based on the available literature, developing an efficient removal method is necessary to keep an eye on microplastics concentration. Therefore, the primary goal of this review is to provide an overview of the possible microplastic removal process from the wastewater and address the issues related to microplastic removal methods. Even though attention on microplastic pollution and its remediation has been increasing, however a comprehensive study on physical, chemical, and biological methods for the removal of microplastics has not been studied. Most of the articles available on open literature focus on any one or two of the removal methods. The present review not only considered different methods of microplastic remediation/removal, but also included the methods of reduction of plastic generation. This review includes the methods to reduce and recycle plastic production by various methods and innovative technology. To the best of our knowledge, there are hardly any article considering microplastic removal strategies including all possible methods and plastic control strategies using modern technology in a single literature. The subsections of the paper provide a more detailed overview of the existing wastewater treatment techniques along with their corresponding functionality principles. Also, considering the importance of achieving many of the sustainable development goals, there is a dire need of revising and reconsidering recent advancement in microplastic pollution for further research. Considering the above facts, the present study aims to (a) study the physical, chemical, and biological methods of removal of microplastics from aquatic environments, (b) study recent remediation strategies, and (c) assess the control strategies for plastic production.

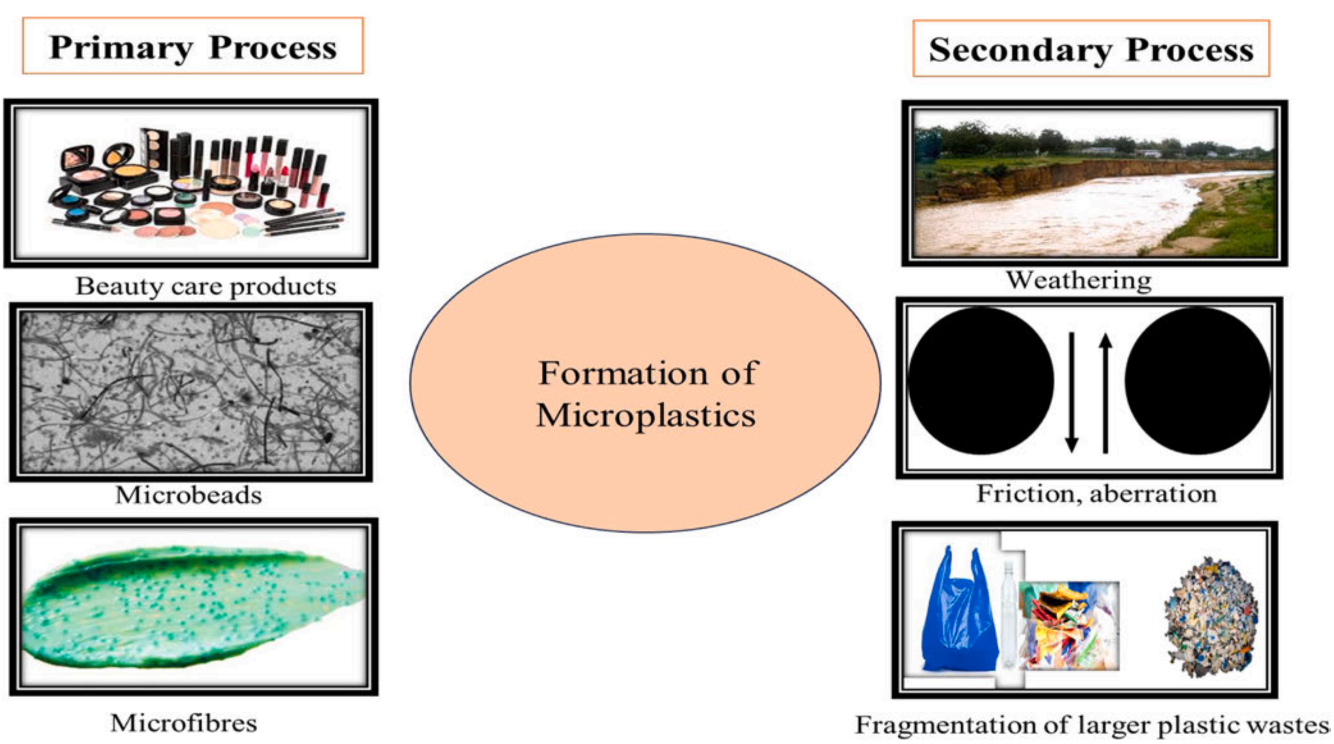

Fig. 1. Primary and secondary processes involved in the formation of microplastics.

2. Research method

This review is based on the research articles retrieved from the Scopus database using different keywords such as microplastics, remediation strategies, aquatic system, wastewater, removal and water, etc. in the search menu of title, abstract, and keywords for years from 2013 to 2024 (Source: Scopus, WOS, Google scholar, ResearchGate, Sciencedirect, etc. searched on 02 August 2024). At first, a combination of search keywords "Water treatment + Microplastics" was applied to sort the relevant articles. Literatures published in English language were selected from 2013 to 2024 (Till August), resulting in 17,300, 1235, 823, and 782 related articles acquired via Google Scholar, Scopus, Web of Science and PubMed, respectively. The keyword microplastics retrieved lots of research articles in different subject areas (Fig. S1). This indicates that the highest number of publications was recorded for environmental science (12,582) followed by agricultural and biological science (3393), chemistry (2607), Earth and planetary science (2256), and engineering (1772) respectively. For environmental science, the number of publications is high indicating this is one discipline that is explored during this decade. However, energy, computer science, immunology, and microbiology have very low numbers of publications, explaining these areas are not much explored. When it comes to document types for the keyword microplastics, research articles got first place among all the article types, indicating that lots of research activities are going on globally (Fig. S2). During 2013–2023, the number of published review articles was higher (2160) than the number of book chapters (671). For the present review, >250 articles are considered for physical, chemical, biological methods and microplastics control strategies for the year of 2013–2024. The maximum number of papers were selected for the year of 2023, followed by 2024 (Fig S3). However, >300 articles were considered for the present review, mostly from recent decades (>90 %). The keywords included were 'microplastic', 'water', 'removal technology', 'removal methods', 'treatment method', 'treatment technology', 'nanoplastics', 'plastics', 'wastewater', and 'MPs'. The review papers, short communications and book chapters are excluded for studying the physical, chemical and biological treatment methods. The research articles were considered for the years of 2013 to 2024.

3. Microplastic removal techniques from wastewater

In general, three methods namely, physical, chemical, and biological can be employed to remove microplastics from aquatic systems (Fig. 2). Such methods are used in wastewater treatment plants to get potable water, and to discharge effluents from industries after treatment. The comparison of various methods of microplastic removal has been explained in Table 1.

3.1. Physical method

Physical treatment methods include the process of removal of microplastics without changing the chemical and biological properties of water or pollutants. Such treatments are done before chemical or biological processes (Ahmed et al., 2021a). Most of the studies include physical approaches that usually follow adsorption, filtration, oil film methods, magnetic separation, froth flotation, etc. (Badola et al., 2022). These approaches are successful in removing microplastics from sewage water and other aquatic systems.

3.1.1. Adsorption

Adsorbents such as graphene oxide and chitins, have been used to demonstrate the superior efficacy of the adsorption approach in removing microplastics from wastewater due to their specific characteristics; biocompatible, and biodegradable nature (Sharma et al., 2020). Further, graphene oxide and chitin-based sponges are also viable choices for the effective removal of microplastics from wastewater (Badola et al., 2022). Adsorption method suggested with the application of coal gasification slag-based adsorbent known to remove microplastics up to 99.2 % (Lv et al. 2024). However, the effectiveness of this technique is constrained by the non-selective features of the adsorption process (Bruyninckx and Dusselier, 2019). Therefore, future research is needed to improve the adsorbent's ability to target microplastics to improve removal effectiveness.

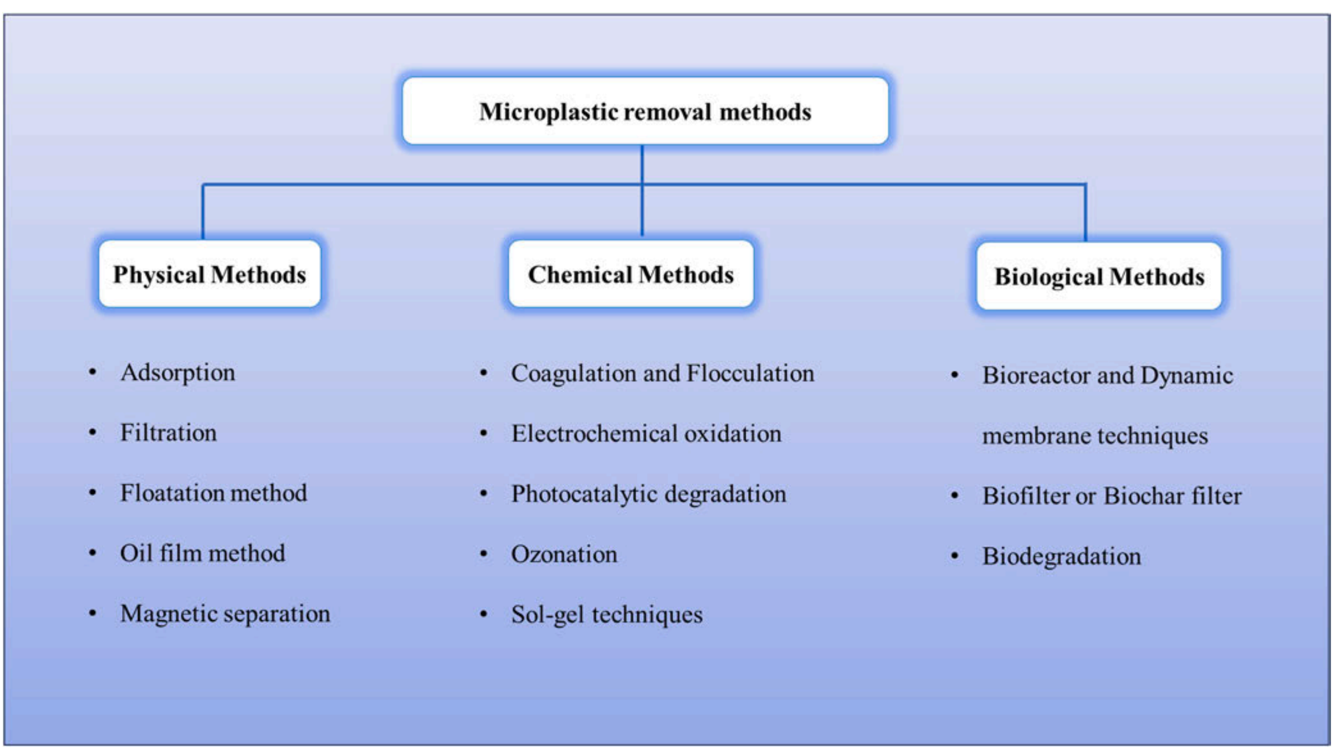

Fig. 2. Methods employed for removal of microplastics from aquatic systems.

Table 1
Comparison of various removal methods of microplastics.

Techniques	Microplastics removal efficacy (%)	Advantages	Disadvantages	References
Disc filtration	43.13–72.50	low energy use, accelerates the removal of microplastics from WWTPs	microplastics' fragment shape is difficult to effectively eliminate	Kwon et al. (2022)
Sand filtration	74–97	simple operation and low cost	efficacy to eliminate small particles is still not clear	Talvitie et al. (2017)
Membrane bioreactor technology	100	removing contaminants at varied concentrations while ensuring high-quality effluent and effective removal	limitations in aeration, membrane fouling, the requirement to supplement bacteria with nutritive ingredients, and expensive cost	Javier et al. (2020); Talvitie et al. (2017)
Photocatalytic degradation	nr*	eco-friendly, long-lasting	requires a lot of energy (ultraviolet light)	Uheida et al. (2021)
Magnetic separation		less waste sludge, high efficacy, high volume	large number of magnetic seeds required, separation of magnetic seeds and particles	Zhang et al. (2021a)
Adsorption removal		high reusability, affordable price, easy to use, and no harmful chemicals	low selectivity, prepared using an adsorbent	
Electrochemical oxidation		high efficiency, degrading a number of organic contaminants, not requiring the addition of chemical agents, and not producing sludge	high cost of electrodes	Chen et al. (2022)
Electrocoagulation	99	energy-efficient, economical, adaptable to automation, effective for removing small microplastics, reduced sludge, no need for chemical coagulants	replacement of the sacrificial anode and cathode passivation on a regular basis	Perren et al. (2018)
Coagulation	17–99	suitable for removing tiny microplastics, and low energy usage,l	Difficult to deal with multiple pollutants at once	Xu et al. (2021); Rajala et al. (2020)
Biochar filters	100	good adsorption capacity	Remove microplastics particle of micrometre size	Siipola et al. (2020)
Ozonation	89.9	low cost and high efficiency	Emission of hazardous substances from incomplete combustion is risky for the environment and people's health	Bui et al. (2020); Hidayaturrahman and Lee 2019
Bioinformatics	nr	environmentally friendly, Cost efficient	lack of experimental data and its validation	Ali et al. (2021); Anand et al. (2022)
Oil film separation	96	simple to use, affordable, and independent of density	hydrophobic surface required, organic contaminants entrainment	Zhang et al. (2021a)
Froth flotation	nr	quick operation, little space needs, adaptability of use, and moderate price	reagents for flotation, a hydrophobic surface, and entrainment of organic pollutants are all necessary	

nr*- not reported

3.1.2. *Filtration*

3.1.2.1. Sand filter. Rapid sand filter effectively eliminates varieties of pollutants (Wang et al., 2021). Microplastics cling to the sand grain's surface and remove the suspended materials (Lusher et al., 2019). The wastewater from the treatment plant is filtered through a series of sand filters consisting of various layers made of different materials and grain sizes. A study employed rapid gravity sand filters examined for microplastics removal from wastewater and showed the removal efficiency ranging from 74 to 97 % (Hou et al., 2021). Rapid sand filter is also known to remove approximately 84–98 % of the microplastics (<10 μm) from tap water (Chabi et al. 2024). Application of granular limestone in rapid sand filtration process can improve the microplastic removal efficiency (Li et al. 2023).

Due to the modest minimum required land area, low water quality sensitivity indicators, and high flow rate, sand filtration has been quickly highlighted as a feasible technology for removing microplastics (Talvitie et al., 2017). Nevertheless, this method is quite expensive due to the series of applications (WHO, 2019). Also, this method is effective in removing microplastics particles having size greater than 200 μm (Sembiring et al. 2021). Effective size of filter media and flow speed is also a key factor for the removal of microplastics (Wulandari et al. 2024).

3.1.2.2. Disc filter. Disc filters are frequently used at wastewater treatment plants as a last polishing procedure to remove particles and associated pollutants in wastewater treatment. Microplastics removal is based on the physical retention of particles in filters and the creation of cakes of sludge inside the filter panels (Ahmed et al., 2021b). Disc filtration is a tertiary treatment process which significantly reduce the number of microplastics in effluent wastewater (Ali et al., 2021). Komorowska-Kaufman and Marciniak (2024) reported the microplastic removal efficiency of 80–98 % through disc filter. However, other research has shown that disc filters with similar mesh sizes can remove microplastics at rates of 89 % (Ahmad et al. 2021). A study conducted by Talvitie et al. (2017) to remove microplastics by employing disc filters, consists of 24 filter panels in the pilot-size disc filter. A cationic polymer and a coagulant based on iron were also used to increase particle recovery. Depending on the pore size, filter design, and water quality the effectiveness of disc filters is defined. Further, additional treatment techniques can be used to increase the effectiveness of disc filters for the removal of microplastics, including flocculation, coagulation, and advanced oxidation (Komorowska-Kaufman and Marciniak 2024).

3.1.2.3. Biofilters or biochar filter. Biofilters are commonly used to remove contaminants from stormwater (Kuoppamaki et al., 2021) and wastewater effluent (Liu et al., 2020). Biofilter consists of different media such as granular activated carbon and anthracite sand and are effective in removing microplastics. Rullander et al. (2024) used bark and biochar for removing different types of microplastic polymers such as polyamide, polyethylene, polypropylene, and polystyrene from the stormwater. They observed that >97 % of the microplastics were retained in the biochar and bark filter. Biofilters made from different plants (*Armeria maritima, Hippophae rhamnoides, Juncus effusus*, and *Festuca rubra*) are effective in removing microplastics having size greater than 10 μm present in stormwater (Johansson et al. 2024).

Biochar is a solid carbonaceous material derived from biomass as a result of a thermochemical conversion process. Recently, biochar has had multiple applications in water and wastewater treatment, soil quality enhancement, carbon sequestration, and as an energy storage device. In addition to sand filters, biochar was another filter medium that successfully removed microplastics through adsorption. Microplastics are retained in biochar filters because of the large size of pores. Between the biochar porous structure, microplastics adsorb through the physisorption process. Experiments performed with activated carbons showed good efficacy toward microplastics removal. Nonactivated biochar is also used for the removal of bigger microplastics. Removal of microplastics through biochar is less expensive, easy to handle, less sophisticated, and cost-effective. However, a greater in-depth understanding of microplastic removal mechanisms is still necessary (Siipola et al., 2020). Biochar can be derived from a variety of materials, such as bark from corn, pine trees, hardwood, and spruce. Several studies documented that biochar can be obtained either separately or together, to remove microplastics. It has been noted that under various circumstances, the majority of using biochar filters demonstrated effectiveness for the elimination of microplastics. The bark of spruce and pine biochar-based adsorbents has proven successful, having a 100 % success rate in eliminating microplastics. This approach is shown to have a good adsorption capacity while having a small surface area. However, these are simply examined for fleece fibres and plastic particles. Additionally, this technique did not considerably reduce microplastics particles at the micrometer scale, and was only beneficial for bigger particle sizes (Siipola et al., 2020). Some other organic materials are often used for the preparation by biochar. Olubusoye et al. (2024) examined the effectiveness of biochar made from pinewood and sugarcane and observed the microplastics reduction efficiency ranged between 86.6–92.6 % from the water. In another study by Ahmad et al. (2023), jujube waste-derived biochar was prepared to examine the microplastic removal efficiency, and it was observed that the prepared biochar can remove >99 % of nylon and ethylene from the water. Biochar prepared from rice husk also exhibited a higher microplastic removal efficiency of 99.96 % from the aquatic environment (Wu et al., 2023). It has also been suggested in a study conducted by Li et al. (2023) that the adsorption by magnetic corncob biochar along with magnetization process can effectively remove 97 % of the microplastics.

3.1.3. Oil film method

The hydrophobicity-based technique for oil film extraction is very effective in removing microplastic particles. Using a canola oil extraction process, researchers isolated microplastics from water and achieved a high recovery of up to 96 % (Zhang et al., 2021a). The density-independent strategy offered a low-risk, cost-effective replacement for previous approaches based on the oleophilic characteristics. Similarly, microplastics were removed from the sea water samples using castor oil, and microplastics average spike recovery was up to 99 %, while their average matrix reduction was 95 % (Mani et al., 2019). A method based on vegetable oil was developed by Saczek et al. (2024)) for extracting microplastics from water samples containing microplastics. Here, separation was carried out by agitating the sample at high speed to produce bubbles. These bubbles get attached with the oil films which are further removed using reagent alcohol. The microplastics removal efficiency using vegetable oil was >98 % (Saczek et al., 2024). The major disadvantage of this process is that the samples with high biogenic loads require one extra step (digestion) before mixing the oil and separating the microplastic particles. Furthermore, the remaining oil traces require an extra cleaning approach that includes ethyl alcohol and hydrocarbons which can hinder oil separation. Oil volume and water salinity are the major factors affecting the efficiency of oil film methods (Saczek et al., 2024).

3.1.4. Magnetic removal

Magnetic separation has been shown to be effective in the removal of microplastics from wastewater because of its great potential to bind with microplastics and its durable magnetic characteristics (Zhang et al., 2021a). This method can effectively eliminate microplastics from water samples (Zhang et al., 2021a). This removal method employs a variety of materials, referred to as magnetic seeds, including magnetic carbon nanotubes and iron nanoparticles. Electrical friction, the formation of hydrogen bonds, and complexation are the controlling factors for magnetic separation (Yang et al., 2022a). With an efficiency of 93 %, magnetic separation is very effective for removing small-sized microplastic particles (Rani et al. 2023). Furthermore, the polystyrene removal efficiency from water using modified Maifanite by rotating magnetic field was observed up to 98.46 % (Shi et al. 2024). The shape and size of the microplastics also have an impact on the separation process, and the presence of other contaminants has a negative impact based on efficacy and selectivity (Jiang, 2018). This method has several advantages: it has better adsorption capacity, reduced sludge waste, and improved separation due to long-range magnetic force. As a result, more in-depth research is needed to increase the effectiveness of magnetic removal.

3.1.5. Froth flotation method

The selective adherence of bubbles to the required minerals is the mechanism underlying the efficient mineral processing technique known as froth flotation (Tao, 2022). The primary element of froth flotation is surface wettability; materials with a hydrophobic outer surface tend to float as froth aggregations, whilst their hydrophilic counterparts are transported as underflow (Zhang et al., 2021b). Plastics are more likely to become embedded with a bubble cluster and usually have a hydrophobic low-energy face (Wang et al., 2013).

Froth floatation with ultrafine bubbles can efficiently remove small microplastics particles such as Polystyrene, Polyethylene terephthalate, Polyvinyl chloride, Polylactic acid and Polybutylene succinate from wastewater (Poolwong et al. 2023). Combining coagulation and floatation in removing microplastics are also good choice for getting better microplastic removal efficiency. Esfandiari and Mowla (2021) observed the removal efficiency of 96.10 % while using Al-based coagulant along with floatation method. Advanced nanobubble flotation technique is very useful in removing microplastics from seawater by promoting bubble-particle collision and increasing attachment probability (Kharraz et al. 2024). Xu et al. (2024) used chitosan (CTS), a natural cationic polymer, was selected to improve the separation of polystyrene using air flotation and observed the removal efficiency up to 96.7 %. Some factors affecting the froth floatation process are electrostatic attraction, types of polymers, hydrophobicity, and bridging adsorption, aeration volume, treatment time, pressure and pH, etc. (Jiang et al. 2022; Xu et al. 2024; Poolwong et al. 2023; Kharraz et al. 2024). Microplastics can accumulate large concentrations of heavy metals, medications, plasticizers, and other persistent organic pollutants (Zhang et al., 2021b). According to study by Pita and Castilho (2017), the introduction of foreign functional groups such as hydrocarbons with aliphatic, aromatic, and chloro-halide rings on microplastics surfaces may affect their capacity to float and induce the hydrophilization of microplastics. Small microplastic particles exhibit enhanced flotation potential.

3.2. Chemical method

Chemical treatment includes the application of different chemicals in a series of reactions to promote the water purification process. In chemical treatment, microplastics present in water are forcefully removed by adding specifically targeted chemicals (Ahmed et al. 2021b). Chemical treatments are often important where microplastics cannot be removed from wastewater by physical and biological methods. Such methods convert the harmful microplastics into less harmful chemicals. Some examples of chemical treatment process are coagulation, flocculation, electrochemical oxidation, photolytic degradation, ozonation and sol-gel technology.

3.2.1. Coagulation and flocculation

The primary objective of the flocculation/coagulation procedure is to separate the pre-existing colloidal particles in the solution by neutralizing their charge, forming floccules, and subsequently removing

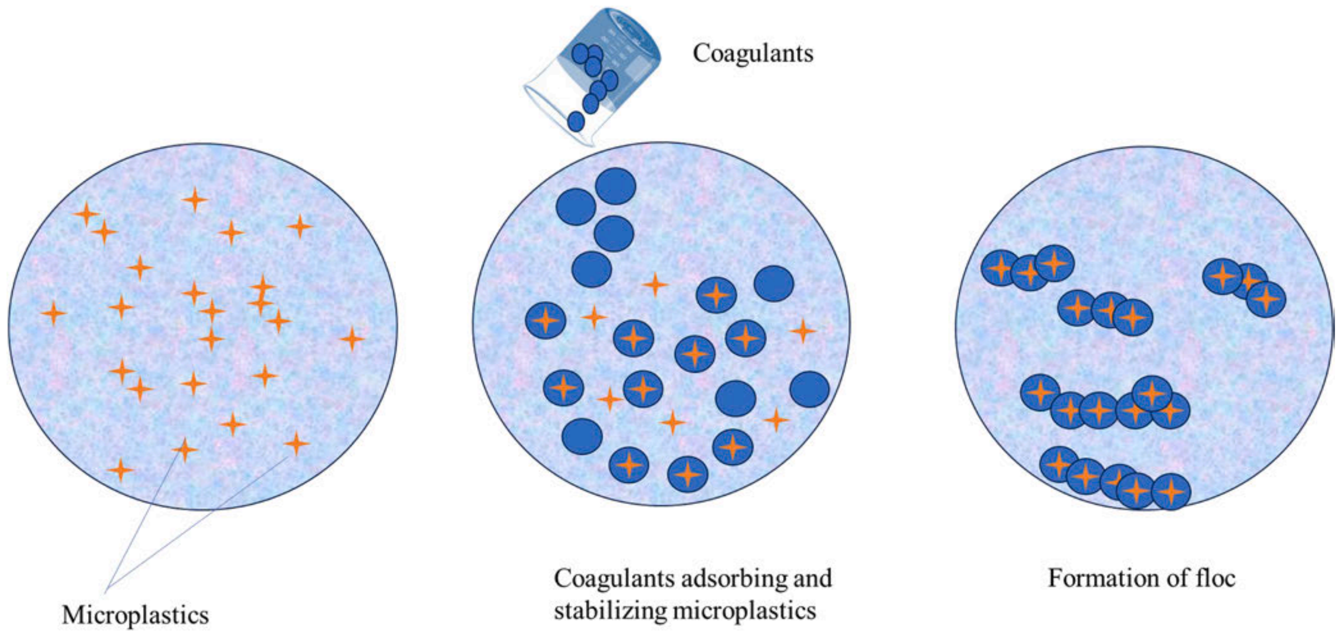

Fig. 3. Coagulation method for the removal of microplastics.

them through sedimentation or filtration (Iwuozor, 2019) (Fig. 3). The most used coagulants are aluminum sulfate ($Al_2(SO_4)_3$), ferric sulfate ($Fe_2(SO_4)_3$) and ferric chloride ($FeCl_3$) (Akinnawo et al. 2023). (Zhou et al., 2021) observed the removal efficiency of $FeCl_3$ for removing microplastics (polystyrene) was 77.83 %. Combining two coagulants, alum and polyacrylamides can effectively remove low-density polyethylene, high-density polyethylene and polypropylene from synthetic stormwater up to 92 %, 84 % and 96 %, respectively (Monira et al. 2021). A combination of coagulation and flocculation methods are often considered as effective for microplastic removal process. However, hybrid methods are often effective for removal of microplastics. Luo et al. (2023) worked on the mechanism of the electro-hybrid ozonation–coagulation, and obtained a good microplastic removal efficiency of >90 %.

Despite being one of the most popular techniques for treating wastewater, the coagulation process has several operational drawbacks, such as a significant amount of sludge exacerbating environmental issues (Osman et al., 2023). Wang et al. (2022) has suggested the conversion of the coagulated material into carbon/iron nanocomposites (CINC) for microplastics removal and their sustainable use. The size, form, and chemical composition of microplastics as well as environmental conditions; the pH, dosage, and the kind of coagulant that aids in coagulation and flocculation are all important factors (Monira et al. 2021). There is currently little research on this method for microplastics, especially wastewater treatment plant. According to Bui et al. (2020), future research should identify the proper coagulant and flocculant aids and conditions for their application in microplastics removal.

3.2.1.4. Electrocoagulation. In contrast to chemical coagulation, electrocoagulation uses metal electrodes to create coagulants electromagnetically. Removing colours, heavy metals, oil, and antibiotics with electrocoagulation is effective (Perren et al., 2018). Metal ions are released into the water stream during electrolysis from sacrificial electrodes. Later, these ions produce in-place coagulants, and electrocoagulant ions generated during electrolysis, react with OH- to form metal hydroxide coagulants, which are the most often utilized coagulants (common metal coagulants; Fe^{2+} and Al^{3+}). According to Garcia-Segura et al. (2017), electrocoagulation is preferred over conventional coagulation due to its non-reliance on chemical coagulant components. Electrocoagulant treated artificial wastewater including polyethylene microbeads at different concentrations (Perren et al., 2018). Microplastic fibres are more effectively removed through electrocoagulation in comparison to fragments (Senathirajah et al. 2023). The effects of initial pH, sodium chloride concentration, and current density on removal efficiency were examined. It was found that electrocoagulation process effectively reduced microplastics by >90 % in the pH range of 3–10. At a pH of 7.5, the highest removal efficiency of 99.2 % was observed.

Subair et al. (2024) showed that electrocoagulation process using Al–Al electrode eliminating microplastics of varying size ranges (0–75 µm, 75–150 µm, and 150–300 µm), achieving removal efficiencies of 90.67 %, 93.6 %, and 94.6 %, respectively. Furthermore, electrocoagulation can be applied successfully with various wastewater properties, resulting in less slush waste and water with fewer dissolved particles. Researchers are intrigued by this cost-effective and environmentally friendly method as a possible substitute for conventional coagulation procedures.

3.2.2. Electrochemical oxidation

Without the need for biological agents, this approach has effectively broken down various organic pollutants, including microplastics, medications, and dyes, into non-harmful byproducts such as carbon dioxide and water vapor (Du et al., 2021). This technique is a cost-effective way of treating wastewater via indirect cathode and anode oxidation, one of the sustainable and affordable methods utilized in the electrochemical oxidation process. Several articles are available in open literature showing that electrochemical oxidation process using different types of electrodes is effective in removal of microplastics. CeO_2 doped PbO_2 composite anode was fabricated for electrochemical oxidation of polyvinyl chloride, and it was observed that the size of the polyvinyl chloride is significantly reduced, and many cracks appear on the surface of the microplastics (Ning et al. 2023). Rare earth element-doped Ti/Sb-SnO2 electrode provides crucial technological support for the electro oxidative removal of microplastics from water with an efficiency of 77 % (Zheng et al. 2024). Falco et al. (2024) used boron-doped diamond (BDD) electrodes to remove polystyrene from the wastewater and observed the removal efficiency of >65 %. Electrochemical oxidation efficiency is affected by the surface area, material, current strength, type, and electrolyte concentration used, as well as by the length of the degradation reaction (Du et al., 2021; Falco et al., 2024).

3.2.3. Ozonation

Ozonation is a tertiary treatment used in wastewater treatment plants to remove any leftover residue of the coagulation process and purify the sewage. Furthermore, the microplastics polymer can be split into functional groups that contain oxygen through ozonation (Bui et al., 2020). Ozonation was explored by Hidayaturrahman and Lee (2019) as a last unit operation in a wastewater treatment plants. Bui et al. (2020) investigated that most (89.9 %) of the remaining microplastics was eliminated by the ozonation process. Ozonation in wastewater treatment plant is known to change the physicochemical properties of water, migration of plasticizer from polymer matrix into water, and structural changes in microplastics present in water (Ziembowicz and Kida, 2024). For improving the efficiency of ozonation process, catalysts including α-MnO_2 and α-FeOOH were synthesized, and it was observed that polyethylene could be efficiently mineralized under the attack of O_3/•OH and decomposition of the polymer is increased under the abovementioned setup (Hu and Hu 2024). The elimination of the microplastics may include a high operational cost. The major drawback of the ozonation process is that an insufficient ozonation process can produce intermediary compounds that pose a risk to public health and the environment due to the production of reactive oxygen species.

3.2.4. Sol-gel technique

A solid strongly cross-linked and an inorganic-organic macromolecule is produced by hydrolyzing and condensing the precursors one at a time during the sol-gel process. This method has been shown to be effective for microplastics with sizes up to 1 mm. It also shows the highest potential to eliminate three to five carbon chain atoms. More widespread use will require proof of its efficacy in natural settings. Herbort et al. (2018) developed a method to remove microplastics from water using organ silanes rather than conventional flocculants. Organ silanes are made up of three reactive groups and one organic group. Microplastics chemical characters and surface chemistry significantly influence the removal procedure and physical interaction with the organ silanes. It is generally observed that the polarity of the polymer reduces the removal efficacy of microplastics; hence it is important to increase the polarity of the organic group to remove highly polar polymers, like polyvinyl chloride. The effectiveness of non-polar polymers is negatively impacted by this, though. It was shown by this research that organ silanes may be more successfully tailored to eliminate contaminants. Because of their remarkable variety and versatility, organ silanes represent a very promising class of compounds for future investigation. The efficacy can be increased by using higher concentrations of organ silanes. Further investigation on the combination of different organ silanes is necessary to effectively remove polar and non-polar polymer blends (Sturm et al., 2021). A hybrid method including the preparation of Ti/Sb-SnO_2 electrodes doped (electrochemical oxidation) with different rare earth elements (La, Ce, Sm or Nd) as active layer by sol-gel method was effective in removing 77 % of the microplastic from water (Zheng et al. 2024).

3.2.5. Photocatalytic degradation

Photodegradation has been considered a very successful and promising technology for treating hazardous organic pollutants, such as microplastics from wastewater (Liu et al., 2019). During this process, semiconductor materials absorb visible or ultraviolet light, which produces free radicals such as superoxide and single oxygen radicals that oxidize the microplastics are used (Zhu et al., 2019). The material absorbs light above the photocatalytic energy of a semiconductor's bandgap. A transition from the valence band to the conduction band of an electron band results in positive holes in the valence band. Ultimately, the microplastics are degraded by the radicals produced by this process, specifically superoxide and hydrogen (Fig. 4). Iron-zinc oxide nanocomposite, produced sustainably, is a significant semiconductor material used in the photocatalytic breakdown of polyethylene (Lam et al., 2021; Surana et al. 2024). Ariza-Tarazona et al. (2023) showed the photocatalytic degradation of polyethylene terephthalate can be achieved using C, N-TiO_2/SiO_2 photocatalysts and the mass losses in this process ranged between 9.35 % and 16.22 %. In addition, the photodegradation behaviour of polyamide microplastics is studied by using polyamide microplastics and $FeCl_3$ as catalyst. The result showed that polyamide microplastics can be almost completely degraded after 10 days of irradiation in $FeCl_3$ aqueous solution (Zhong et al. 2024). The factors affecting the rate of photocatalytic degradation are the solution's pH, the termination rate, size of microplastic particles. time and the ease of generating free radicals necessary for extracting hydrogen atoms from polymer chains (Xie et al. 2023).

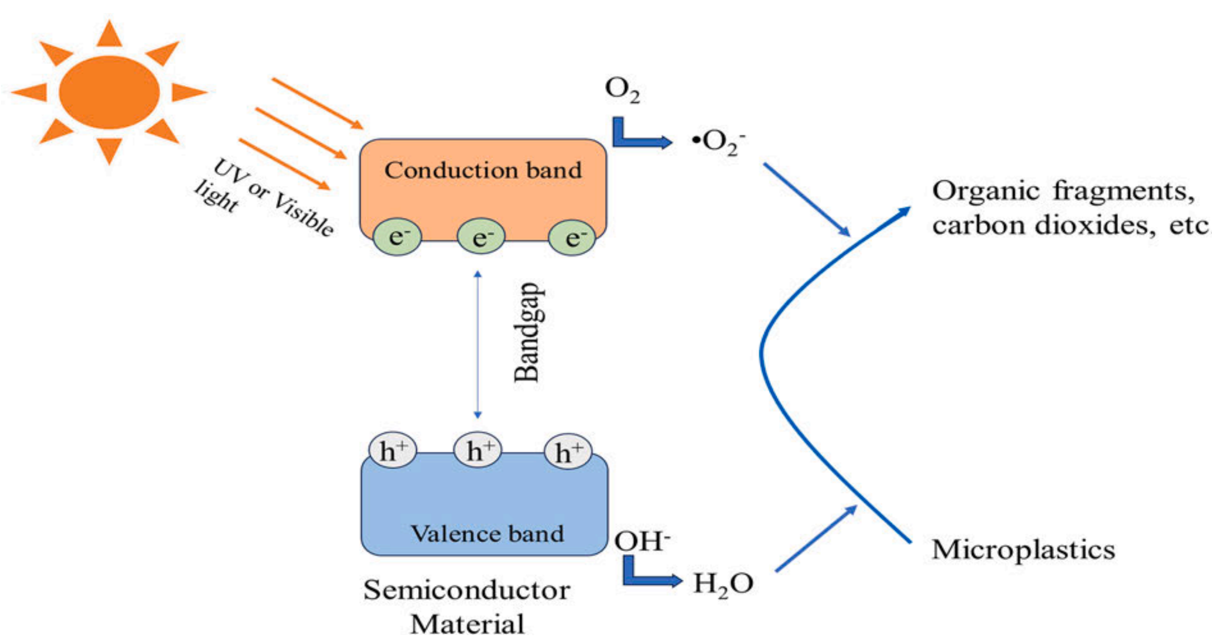

Fig. 4. Photocatalytic reduction process for the removal of microplastics.

3.3. Biological method

Biological approaches use various plants and animal species to solve the issue of microplastic contamination present in aquatic systems and wastewater. It has been investigated how organisms can contribute to degrade microplastics that are present in water and wastewater. Studies are also ongoing on biological methods for microplastic removal. Scientists are investigating possible treatment methods to eradicate microplastics via decomposition by employing different biological species (Table 2).

3.3.1. Bioreactor and dynamic membrane techniques

Using dynamic membranes is one way to eliminate low-density, non-biodegradable microplastics sources because of their low cost, ease of maintenance, and minimal energy consumption (Li, 2018). Li et al. (2018) examined how influent flux and particle concentration affected the diatomite ledge's ability to filter simulated wastewater using dynamic membrane with 90 mm of secondary mesh. The formation of dynamic membranes is encouraged by higher concentrations of microplastics and pollutant fluxes. However, membrane bioreactors have a higher capacity for removing micro-sized plastics than simple dynamic membranes (Lares et al., 2018). The membrane bioreactor's capacity to successfully remove a wide range of complicated industrial wastewaters confirms the technology's ability to handle strong contaminants microplastics and polymeric debris. Microplastics are successfully removed with the help of membrane-based technology from aquatic systems. Egea-Corbacho et al. (2023) observed the microplastic removal efficiency of 99.69 % with the application of membrane bioreactor-based technology. Anoxic/aerobic membrane bioreactor technology not only reduces microplastic content in the wastewater but also causes change in physicochemical properties in microplastics (Wang et al. 2024). Membrane bioreactor (MBR) technology has emerged as a leading solution for advanced wastewater treatment, ensuring high removal efficiency for both conventional and emerging contaminants while also enhancing resource recovery (Cairone et al. 2024).

3.3.2. Biodegradation

3.3.2.5. Fungal degradation. Most organisms that comprise fungi are either obligatory parasites, opportunistic parasites, or saprotrophs. Due to their remarkable adaptability, they may flourish in a wide range of terrestrial and aquatic ecosystems and many environmental settings. They can withstand various hazardous chemicals and metals and produce various enzymes from outside the cell, including organic biosurfactants like hydrophobins that can break down complex polymers into simpler monomers. It also supplies electrons and carbons to the microorganisms responsible for the breakdown and mineralization of complex pollutants (Olicón-Hernández et al., 2017). Fungi that break down polyethylene mostly include *Aspergillus* and *Cladosporium*. Their main source of carbon is polyethylene, which they subsequently decompose using an enzyme outside of cells. By decreasing the hydrophobicity of plastic particles, these fungi promote the formation of various chemical bonds. The development and degeneration of various microplastics are significantly influenced by the maximum number of these fungi, which have a wide distribution and efficient reproduction (Dey et al., 2023).

According to a study by Das et al. (2018), low-density polyethylene can be biodegraded by *Aspergillus* and *Fusarium* species. *Aspergillus flavus*, a type of fungus strain that was discovered among piles of plastic debris near the coast, showed efficacious high-density polyethylene degrading properties, whereas *Aspergillus tubingensis* efficiently degraded polyethylene (Devi et al., 2015). Research on this area is now underway where various fungal strains work in different environmental circumstances to break down microplastics. Research on fungal groups that can break down microplastics has benefited immensely from the introduction of omics and molecular tools such as polymerase chain reaction, in-vitro transcription, and high-throughput sequencing (Table 3).

3.3.2.6. Bacterial degradation. Bacteria are ubiquitous and diverse class of microorganisms that are present in soil, water, and the atmosphere, among other settings (Yuan et al., 2020). They have a well-known ability to degrade contaminants like microplastics, and are crucial to the cycling of nutrients. Several studies have focused on using pure bacterial cultures in carefully monitored lab settings to assess the microplastics degradation. Most of these bacterial cultures can be found in collections of cultures or obtained via enrichment culture from sludge, sediment, and wastewater. Researchers can study metabolic processes and use pure lines to assess their effects, unlike ecological factors that influence microplastic breakdown. Furthermore, this method allows for tracking the entire microplastic process through active bacterial changes. The ability of bacterial isolates to degrade microplastics was examined in studies. Researchers examined a mangrove silt bacterial culture's ability to degrade polypropylene after it had been purified. Research indicates that two strains of *Rhodococcus* sp. Type 36 and *Bacillus* sp. Type 27 may support polypropylene polymer of microplastic losses of 4.0 % and 6.4 %, respectively (Yuan et al., 2020). Bacteria were evident on the surface of the treated polypropylene due to the numerous pores and other irregularities.

Table 2
Bacterial species used for the degradation of microplastics.

Bacterial isolates	Sources	Degraded polymers	Degradation (%)	Incubation time (days)	References
Bacillus sp; Paenibacillus sp.	municipal landfill sediment	PP	14.7	60	Park and kim (2019)
Sporosarcina Globispora	mangrove sediments in Peninsular Malaysia	PP	11	40	Auta et al. (2017)
Bacillus cereus	mangrove sediments in Peninsular Malaysia	PP	12	40	
Actinomycetes sp; Pseudomonas sp	polypropylene waste	UV and HNO_3 polypropylene (PP)	nr*	15 and 45	Sepperumal and Markandan (2014)
Bacillus	mangrove sediment	PP	4	40	Auta et al. (2017)
Comamonas acidovorans	nr*	PURs	100	8	
Rhodococcus	mangrove sediment	PP	6.4	4	
Lysinibacillus sp	polluted soil samples	PE, PP	4 and 9	26	Anaand et al. (2022)
Chelatococcus sp.	compost	LDPE	44.5	88	Jeon and Km (2013)
Microbial consortia; including Aneurinibacillus sp; and Brevibacillus sp	sewage treatment plants (STP)	LDPE, HDPE, PP	47, 58 and 56	140	Skariyachan et al. (2018)
Bacillus thuringiensis	compost	PP and poly l-lactide	12	15	Anaand et al. (2023)
Bacillus sp	sediment samples	PP	4	nr*	Auta et al. (2018)

nr*- not reported; PVC-polyvinyl chloride; PE-polyethylene; LDPE-low-density polyethylene; PP-polypropylene; PURs-polyurethane; HDPE-high-density polyethylene.

Table 3
Fungi-mediated degradation of microplastics.

Fungal isolates	Sources	Degraded polymers	Incubation time (days)	References
Penicillium simplicissimum	dumpsite	UV-treated PE	nr*	Sowmya et al. (2015)
Aspergillus niger	waste dump	LDPE	84	Nowak et al. (2012)
Fusarium spp	plastic waste disposable site	LDPE	28	Joyti and Gupta (2014)
Aspergillus favus VRKPT2	marine coastal area	HDPE	30	Devi et al. (2015)
Aspergillus flavus	guts of wax moth	HDPE	28	Dey et al. (2023)
Aspergillus niger	soil from waste disposal site	PE	30	Deepika and Jaya (2015)
Aspergillus terreus *Aspergillus sydowii*	mangrove dumpsite	PE	60	Sangale et al. (2019)
Verticillium lecanii	soils	PE	nr	Ekanayaka et al. (2022)
Xepiculopsis gramineae	plastic debris on a shoreline of a lake	PU	nr	Brunner et al. (2018)
Phanerochaete chyrsosporium	soils	LDPE	nr	Yang et al. (2013)
Aspergillus tubingensis	soils	PU	nr	Khan et al. (2017)
Zalerion maritimum	marine sediments	PE pellets	28	Paço et al. (2017)

nr*- not reported; PVC-polyvinyl chloride; PE-polyethylene; PET-polyethylene terephthalate; LDPE-low-density polyethylene; PP-polypropylene; PU-polyurethane; HDPE-high-density polyethylene.

3.3.2.7. Bioremediation by marine organisms. A report titled "Interactions Between Organisms and Marine microplastics - A Call for Research" was released by Harrison et al. (2011) to highlight the tremendous potential of microorganisms, including bacteria, archaea, and picoeukaryotes. The interaction between synthetic microplastics and marine organisms was investigated. Much research describes the biological degradation of natural and manufactured microplastics (Ahmed et al., 2018). Environmentalists from Australia studied the size and fragmentation of polyethylene polymers absorbed by Antarctic Krill, a type of planktonic crustacean (*Euphausia superba*) has the tendency to remove the polymers (Dawson et al., 2018). The research findings indicate that tiny microplastics are easily broken apart in a biological setting. Nonetheless, the fragmentation mechanism, the character of microplastic-zooplankton interactions, and the biota-facilitated biodegradation process remain incompletely understood. Using two distinct kinds of native marine communities - *Souda and Agios consortiums*, Cocca et al. (2020) reported the ability of the communities in removing secondary High-density polyethylene polymers of microplastics from ocean water. Based on the results of the weight reduction measurements, the *Souda consortia* were more efficient. The process involves both enzymes and microbe genes.

3.3.2.8. Phytoremediation. The enzymes are often used to their full potential biologically to break down polymeric materials by employing algae (Chia et al., 2020). Numerous processes: including hydrolysis, corrosion, fouling, and penetration, indicate how algae decompose the microplastics (Chia et al., 2020). The key advantage of this system over the bacterial one is that the microplastics are found in environments that are rich in carbon supplies, but the bacteria require a rich carbon source for development (Bergkessel et al., 2016). Enzymes called ligninolytic and exopolysaccharide are produced when algae cling to plastic surfaces in wastewater streams, initiating plastic degradation. These polymers accelerate growth, serve as a carbon source, and improve cellular proteins and carbs. Lately, low density polyethylene sheets that have been infested by algae have been identified using scanning electron microscopy's ability to detect surface degeneration or disintegration (Sanniyasi et al., 2021). It was also shown that *Oscillatoria subbrevis* and *Phormidium lucidum* may colonize and degrade low density polyethylene without pretreatment or prooxidative chemicals (Sarmah and Rout, 2018). Terephthalic acid and polyethylene terephthalate (PET) films can be broken down by PET hydrolase, which was created by genetically modifying the green microalga *Chlamydomonas reinhardtii*. A similar modification to *P. tricornutum* produced PET hydrolase, which exhibits catalytic activity for both PET and the PET glycol copolymer (Ma et al., 2018). A study on biodegradation processes of polyethylene particles was carried out using microalgae *Chlorella vulgaris,* which was able to remove about 84 % of the particles (Nasrabadi et al. 2023). An application of five marine microalgae strains viz., *Chloroidium saccharophilum, Picochlorum maculatum, Amphora* sp., *Hymenomonas globosa* and *Limnospira indica* in testing the biodegradation ability of Low-Density Polyethylene showed alteration in crystallinity, thermal stability and structure suggesting that algal remediation technique can reduce microplastic pollution (Gowthami et al. 2023).

We currently know very little about how higher plants absorb and store microplastics. Nonetheless, new research indicates that certain plants possess the ability to accumulate micrometric and submicrometric sizes of microplastics generated from soil. Plants absorb microplastics through their roots, store them there, and then transfer them to other parts of the plant. Cleaning up microplastic-contaminated water may be accomplished by using phytoextraction and phytofiltration, two phytoremediation techniques. To remove contaminants from aqueous waste streams and groundwater, plants are employed in phyto-filtration, also known as rhizo-filtration. Either the plant roots absorb the contaminants, or the chemicals are adsorbed on the root surface. According to research by Abbasi et al. (2021), polyethylene terephthalate particles are exposed to naphthalene and phenanthrene for adsorption. Results conclusively showed that the average concentration of naphthalene adsorbed to polyethylene terephthalate was higher (96.89 %) than that of phenanthrene (27.27 %). However, polyethylene terephthalate particles desorb 21.65–29.17 % of the sorbed adsorbates. The exudate from the simulated wheat roots contains phenanthrene and naphthene. Three types of wheat root exudates were identified, and the polycyclic aromatic hydrocarbon contents were likewise desorbed at comparable amounts by the polyethylene terephthalate particles. Ultimately, the results show that polyethylene terephthalate polymers cause the entry of polycyclic aromatic hydrocarbons into a rhizosphere zone. Zhang et al. (2022) reported that there is no evidence of plant injury or exposure to bisphenol S, a pollutant that is becoming more and more concerning. This study aimed to determine bisphenol S translocation and phytotoxicity in plants exposed to polystyrene polymer. Plants may withstand co-contamination with bisphenol S and polystyrene, as the results showed that bisphenol S and polystyrene did not influence plant growth.

A study by Yang et al. (2022b) showed that heavy metal and microplastics contamination are common in freshwater ecosystems. Nevertheless, studies on how they interact to influence aquatic vegetation are scarce. This work investigated the effects of 50 mg/L of polypropylene and 0.01 mg/L of cadmium (Cd) concentration for around 15 days. Duckweed may be better adapted to contaminated water if researchers examine the interactions between Cd, polyethylene, and polypropylene and how these interactions affect the microbial community in the plant's rhizosphere. This research may also provide new insights into employing duckweed for environmental remediation. A few days later, scientists studied the rhizosphere of duckweed, looking at its physiology, ultrastructure, and microbiota. Two essential interactions between microplastics and the floating aquatic macrophyte L. *minor* are shown by research by Rozman et al. (2022), and they are vital for developing a phytoremediation method. These interactions are caused by microplastic adhesion to plant tissues and their effects on L. *minor*. Considering the long-term effects of microplastics on plant development and metabolic markers, L. *minor* might be resistant to high microplastics concentrations.

Kim et al. (2024) demonstrated the use of two aquatic plants (*Iris pseudacorus* and *Lythrum anceps*) to reduce the microplastic content in the aquatic environment. They observed a significant reduction in the microplastic content in the aquatic system due to their possible adsorption in the plant's root. Another study was performed using two plant species *Cyperus papyrus* and *Pontederia sagittata*, to remove the microplastics from the urban ponds. These two plants were capable of removing 61.6 - 82.2 % of microplastics from the ponds.

All the studied methods have the microplastic removal efficiencies ranged between 74 and 99.2 %, 65–99.2 % and 77–100 % for physical, chemical and biological methods, respectively (Fig. 5). Among the three physical, chemical and biological methods, biochar filter, oil film methods, electrocoagulation, bioreactor and dynamic membrane techniques are more effective in removing microplastics. The efficiency of biochar filter is highest and ranged between 99 % 100 %.

4. Bioinformatics and genetic tools

Bioinformatics has evolved into a potent method for quickening the biodegradation of plastic debris, including microplastics particles. Environmental Contaminant Biotransformation Pathway Resource and the University of Minnesota Biocatalysts/Biodegradation Database are two examples of several types of databases. A database about biodegradation pathways has been created to evaluate the biodegradation process by offering information on the metabolic pathway. These databases and computational methods offer a framework for developing a novel strategy for the degradation of plastic by helping to identify the enzymes involved in a desired metabolic pathway and help to predict the biodegradation pathways of hazardous substances (Ali et al., 2021). Despite all these advantages, the primary disadvantage of bioinformatics is the lack of experiments and the validation of that data—both of which are critical for further investigation. Furthermore, there is a big difference between the different kinds of bacteria that break down synthetic polymers and the enzymes that break down microplastics.

Using gene editing methods, the expression of specific genes has been edited into the genomes of bacteria, flora, and fauna (Tang et al., 2020; Mandal et al., 2022). Transcription activator-like zinc finger proteins and effector nucleases are two examples of different types of gene removal tools. The damage and benefit of function studies that alter several gene expressions are also aided by altering an interesting gene by genome editing. This approach can be used to successfully add genes for enzymes involved in the degradation of microplastics, such as PET, hydrolase, esterase, laccase, and depolymerase.

5. Microplastics- control strategies

The management of microplastics can be achieved through a variety of both immediate and long-term strategies. Every technique has disadvantages, including high expenses. Therefore, it's crucial to consider a variety of factors while selecting a strategy, including the structure of the nation, its economic status, the kind of microplastics that have been released, the availability of substitutes, and the local desire to shift away from a plastic-dependent economy. It is always recommended to reduce, recycle and reduce the use of plastics to reduce the microplastic pollution. However, following approaches may be adopted to reduce the use of plastics.

5.1. Creating public awareness

Plastic consumers are not interested in recycling and single-use of plastic because of easily availability, affordability and conveniency of virgin and unused plastics (Northen et al. 2023). Mostly people are not concerned about the ill effects due to plastic wastes. For changing the attitude of the consumer, it is important to create public awareness. In many countries like Japan, Taiwan, UK and Hong Kong, four approaches, community-based education, government-based education, business-based education, and school-based education are implemented to cope up with plastic pollution (Chow et al. 2017). Furthermore, in India, plastic containers are generally made from mixed plastic polymers; hence are often difficult to segregate. In Japan, the plastic containers are made from a single type of polymers like PET bottles, PP bottles etc.; hence are easy to segregate after use (Chow et al. 2017).

5.2. Reducing, recycling and reusing plastic wastes

One of the best ways to stop traditional plastic and microplastics

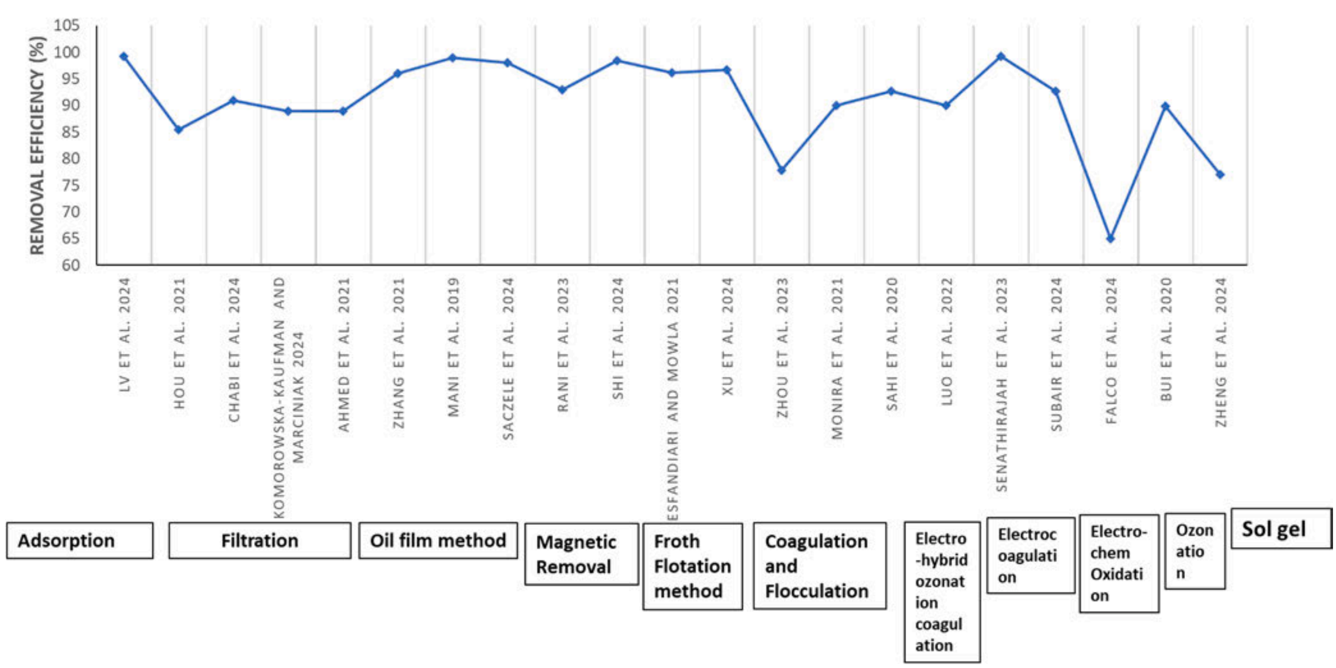

Fig. 5. Microplastics removal efficiency through different physical and chemical treatment processes.

goods from being released into the environment is to reduce their use and manufacturing (Yang et al., 2023). Because of this, therapy is usually not preferred to prevention. One example of this approach is the decrease in microbeads utilized in manufacturing medications and personal hygiene products (Prata, 2018). Although some opponents argue that this technique only reports one form of microplastics pollution, it can nevertheless have a long-lasting effect on minimizing the contamination of water systems with microplastics waste (Faltstrom and Anderberg, 2020).

Using and recycling plastic products is a very effective way to manage plastic waste. Recycled plastics are always more sustainable than the virgin and unrecycled plastics. Using the plastic wastes in landfills can create soil and underground water pollution and may cause several health hazards. Hence, the plastic wastes are reused in various sectors such as fabric, apparel, building materials, household goods, and fuel conversion after four basic recycling techniques. The recycling techniques include primary, secondary, tertiary and quaternary methods (Oladele et al. 2023). Primary methods include mechanical methods such as sorting, shredding, cleaning, processing, and milling. Secondary recycling technique includes remelting and reprocessing of plastic wastes for further application. Tertiary recycling techniques are basically chemical-based processes that convert plastic polymers into its monomeric form to produce new products. Such chemical-based processes include pyrolysis, hydrolysis, methanolysis, aminolysis, etc. Quaternary recycling technique includes the processes of recycling of plastic products which generate energy. Debele et al. (2024) suggested the use of low-density polyethylene plastic waste for flexible paver tile construction for outdoor application. Plastic wastes may also be used in construction of cement (Jaber et al. 2023), fired clay bricks (Idrees et al. 2023), construction and value-added building materials (Ahmed 2023). Waste plastic may also be used as alternate fuels having promising efficiencies. Plastic-based oils (Li et al. 2023), naphtha and gas (Kabeyi and Olanrewaju 2023) may be produced by the thermal and catalytic degradation of plastic wastes and used as alternative fuels. Moreover, Luo et al. (2023) suggested to use the plastics wastes for making value-added carbon materials such as carbon nanotubes, graphene, carbon nanosheets, carbon spheres and porous carbon by oxygen-limited carbonization, catalytic carbonization, the template-based method, and pressure carbonization.

5.3. Application of bioplastics

Innovative solutions and additional work are needed to overcome plastic pollution and progress in plastic recycling. Simple volumetric hydrothermal treatment was also found to be inefficient for recycling plastic. According to Osman et al. (2023), bioplastics, also known as biodegradable plastics, offer a practical substitute for conventional microplastics in a range of uses. Polyhydroxyalkanoates, other food and pharmaceutical packaging materials, and crops and soil have already been protected by mulching films formed of these polymers in horticulture and agriculture (Song et al., 2009). Due to their strength and lightweight, bioplastics are employed in data storage, laptop and smartphone screens, and other electronic equipment. It can also be used in the locomotive industry to cover seats and airbags (Osman et al., 2023). As a result, bioplastics have a wide range of effective applications.

6. Conclusion

An increasingly concerning class of organic pollutants known as microplastics has drawn the attention of academics since 2014. The increasing impact of microplastics makes it imperative to discover sustainable ways to reduce their presence in the environment and mitigate their detrimental effects. This overview centres on the different kinds and sources of global microplastics. Microplastics can be discovered in a wide variety of aquatic bodies, however the majority (80 %–90 %) of environmental contamination comes from land-based sources. The research looked at several microplastics control strategies (chemical, biological, and physical). The removal methods including oil film separation, froth flotation, coagulation, filtration, magnetic separation, filtration, biochar filter and bioremediations are effective in removing the microplastics. All the microplastics removal techniques have several advantages and disadvantages. Among all the methods, biochar filter is most efficient (removal efficiency 99–100 %) in removing microplastics from wastewater. For reducing the production of plastics, crating public awareness is very important. Several research are available suggesting the recycling and reusing the plastic wastes in productive ways. Plastic wastes can be used in value added material, building and construction materials, fabrics and fuel generation. Furthermore, it is recommended to use bioplastics as best alternative. Furthermore, a coordination between policymakers, management, common people and industrialists are necessary for proper implementation of microplastic removal methods and control strategies.

7. Future perspective

To adapt removal strategies for industrialization, extensive experiments are needed. The characteristics of microplastics will be one of the new research areas in the coming years. Application of biochar filter can bring revolutionary development in microplastic removal methods. There are numerous barriers and limitations to using microorganisms for microplastics biodegradation however, microplastics can be circumvented using different genetic modifications.

However, research on the effectiveness of genetically modified bacteria in real-world environments is scarce, and most of these studies have only been conducted in lab settings. Furthermore, very little is understood about the many enzymes and metabolic processes. Subsequent research on microplastics must address several issues and close several research gaps. Understanding microplastics immediate and long-term harmful effects on individuals and the environment is also necessary to develop workable alternatives to disposable masks and the plastic waste generated by the healthcare industry. Microplastics can be more effectively isolated from other pollutants to produce beneficial byproducts, but deciding what will happen to them in the environment is still necessary. Enhancing the quality and efficacy of plastic alternatives should also be a priority. Combined materials such as bioplastics with microplastics create a treatment technology to improve removal efficiency and minimize side effects. In addition to considering financial and infrastructure limitations, a strategy to reduce plastic consumption should also aim to eliminate microplastics and enhance environmental conditions in a sustainable manner.

Moreover, the microplastic pollution can be controlled by reducing, reusing and recycling the plastic-based products. Several methods are available for the same, but they are not implemented due to lack of collaboration between researcher and industries. Plastic wastes can be effectively utilized with the help of coordination among researchers, policymakers, industrialists and plastic consumers.

CRediT authorship contribution statement

Lovely Dayal: Writing – original draft. **Krishna Yadav:** Writing – review & editing. **Uttiya Dey:** Writing – review & editing. **Kousik Das:** Writing – review & editing. **Preeti Kumari:** Writing – review & editing, Writing – original draft. **Deep Raj:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Rashmi Ranjan Mandal:** Writing – review & editing.

Declaration of competing interest

Authors declare that there is no conflict of interest. The authors declare that they have no known competing interests that are relevant to the content of this article.

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Supplementary materials

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Further reading

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Plastic recycling: A panacea or environmental pollution problem

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Increasing plastic waste is a critical global challenge to ecological and human health requiring focused solutions to reduce omnipresent plastic pollution in the environment. While recycling has been touted as one solution to counter plastic waste and resource utilization, it has been largely ineffective in offsetting the impact of rising global plastic production of more than 400 million metric tonnes annually, due to low global recycling rates of only 9%. Over three decades since implementing plastic resin codes, recycling has favoured thermoplastics, neglecting thermoset plastics. There is a constant need to enhance overall recycling efficiency by exploring advanced methods, as enormous gaps exist in fully unlocking the potential of plastic recycling. We identify critical gaps associated with plastic waste recycling and its potential environmental impacts. We discuss substantial progress in recycling technology, designs-for-recyclability with controlled chemical use, and economic incentives to expand markets for recycled plastics and to curb plastic leakage into the environment. Additionally, we highlight some emerging strategies and legally binding international policy instruments, such as the Global Plastics Treaty that require further development to reduce plastic waste and improve plastic recyclability.

The versatile properties of plastics, in contrast to traditional materials such as paper, glass, and metals, facilitate innumerable applications across various sectors, including automobiles, agriculture, electronics, packaging, and healthcare[1,2]. For example, the incorporation of plastic in various vehicle components reduces weight and enhances performance in automobile industries. Our growing reliance on the convenience of consumer plastics has resulted in increased global production and consumption leading to unprecedented plastic waste generation and widespread plastic pollution. However, our infatuation with plastics is weakening due to its associated risks to environmental and human health[3,4].

Globally, more than 9200 million metric tonnes (Mt) of plastic have been produced to date. Of this, a significant 6900 Mt has not undergone any type of recycling, resulting instead in accumulation in landfills or dispersal within the environment. This represents a missed economic opportunity and a substantial detriment to the environmental health[5]. To sustain the viability of this multi billion dollar material, it is crucial to address the complexity of plastic waste and take transformative steps to redesign plastic products focusing on sustainability and end of life (EoL). Among the recently available options to manage plastic waste are (1) landfilling (waste to landfill), with its finite capacity, risks leaching toxic chemicals into the surrounding environment, (2) waste to energy through incineration with the potential to release hazardous chemicals and gases (e.g., dioxins and furans), and (3) recycling plastic waste into new products[6,7] (Fig. 1). Plastic waste in landfills is a reflection of unrealized economic potential and harm inflicted upon the environment. While energy recovery from plastics offers convenience without the labour intensive sorting required for recycling, it limits material recovery to low energy conversion and intensifies atmospheric pollution and global warming. However, emerging carbon capture technologies in exhaust gases may be used so that CO_2 emissions can be minimized[6]. Conversely, recycling presents an opportunity to address the challenge of increasing global plastic waste.

Plastic recycling encompasses the entire process from waste collection to reprocessing into valuable form[8] (Fig. 1). Plastics can undergo mechanical or chemical recycling to maintain their original chemical structure, or deliberately alter the chemical composition of the material, respectively[9,10]. Currently, mechanical recycling dominates plastic waste management[11,12], with polyethylene or polythene (PE) and polyethylene terephthalate (PET) being the most commonly recycled[8,13] and valuable post consumer plastics globally. Plastic recycling is performed using different approaches including primary, secondary, tertiary, and quaternary recycling[6,8]. A small fraction of mechanically recycled plastics undergo closed loop material recycling to generate identical products as the original plastic and contribute to primary

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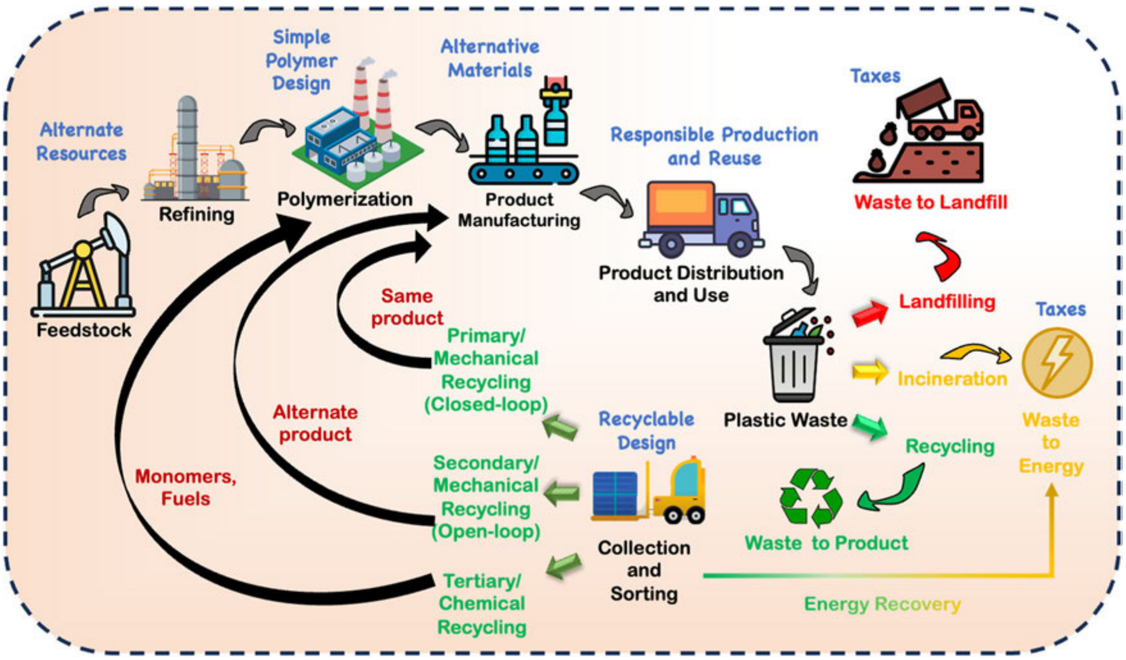

Fig. 1 | Schematic showing the plastic life cycle (black), different plastic waste handling methods (landfilling, incineration, and recycling), approaches to recycling (green), and solutions to achieve sustainability (blue). Artwork for this figure is original and created by the authors.

recycling. As a result, closed loop recycling relies on high quality waste inputs[14], with pre consumer manufacturing waste forming a crucial component[6]. Additionally, open loop recycling creates products serving different purposes than the original material that enters into alternative markets[11]. The process of open loop mechanical recycling can potentially lead to secondary recycling opportunities. Conversely, tertiary, or chemical cycling practices advance methods to depolymerize and recover monomers, and hydrocarbon products through pyrolysis, and gasification[15]. Chemical recycling, while efficient for mixed plastic waste, is quite limited due to high energy requirements and intense reaction conditions. Besides, a major burden of chemical recycling technologies such as gasification or pyrolysis is the need to clean the downstream output to protect the equipment and keep the product valuable[16]. Further, the quaternary approach involves energy recovery by incineration, especially from mixed plastic waste instead of diverting it to landfills[6].

Theoretically, most polymers are recyclable and some even have desirable cradle to cradle lifecycles, offering opportunities for a circular plastic economy[12,17]. Here, we discuss some major challenges of recycling such as the complexity of plastic products themselves, market forces that make fossil fuel derived virgin plastics cheaper than recycled plastic feed stock, the negative environmental, and social impacts, and inconsistent global policies, including the Global Plastics Treaty[18], that influence inter national efforts for effective closed loop plastic recycling[19]. Additionally, we call for prioritizing reduction in plastic production, consumption, and exploring alternative sustainable materials to tackle rising plastic waste[20,21].

Challenges of plastic recycling

Acknowledging the presence of EoL plastics is crucial in addressing the intricacies of plastic recycling. While recycling is widely touted as a pro mising pathway to achieving a plastic waste free future, there remain sub stantial barriers to making this a reality. For example, current global recycling rates, at only 9%, are simply ineffective in the face of increased plastic production. Over 400 Mt of plastics is produced annually[2], primarily as single use items, accounting for more than 50% of consumer based plastics, which are difficult to recycle[22,23]. The intrinsic polymer and pro duct design flows of plastic impede their EoL recyclability. Despite the recyclability of most consumed thermoplastics, only a small fraction of them find their way into the recycling stream. Besides, several plastics are incompatible during recycling resulting in a phase separate mixture adding to the recycling cost and reducing profitability[6]. Meanwhile, the phase separation of the mismatching plastic waste stream can be controlled by polymer compatibilizers such as block copolymers, and graft copolymers[24]. The introduction of compatibilizers stabilizes the immiscible mixture and allows their interaction to produce advanced material[12,13].

Contemporary recycling techniques predominantly address thermo plastics, omitting a substantial fraction of plastic types lacking circular design. Thermoset plastics exemplify this issue, where their valued rigidity from covalent cross linking also confers significant recycling resistance[12]. While it is possible to grind into fine powders for certain downgrade applications, recycling thermosets, which currently constitute one third of the total plastic manufactured, requires a distinct approach compared to thermoplastics[25]. Similarly, elastomers primarily composed of tires, represent one of the rapidly expanding industries, and encounter an uncertain fate[24,26]. Additionally, composite plastics, integrating polymers with fibrous substances such as fiberglass or carbon fibre, are increasingly used across various industries but present substantial separation hurdles. These challenges underscore the imperative for research into the design of easy to recycle plastic materials[17,27].

The complexity and diversity of plastic compositions, exacerbated by chemical additives blended for versatility, lead to a low recycling rate due to the difficulty in recycling different grades together without degrading properties[11]. For instance, reprocessing different colours of 100% recyclable PET[28] together can lead to lower quality recyclate[19,24]. High value transparent plastics are preferred and hold higher market value, while pigmented ones may be discarded. Therefore, recycling necessitates extensive sorting facilities to maintain the quality of the end product. A notable challenge to sorting lies in the complex composition of most plastic waste generated today, com pounded by contamination with labels, coatings, and food remains[8,29]. The immiscible plastic waste, combined with diverse materials, questions the efficacy of current recycling techniques, which are more inclined to pure waste polymers requiring efficient waste collection and extensive sorting[24]. Although sorting waste at the source has generally improved, the sorted waste is often underutilized or repurposed ineffectively[30]. If the waste stream is too contaminated, it is not recycled and diverted to landfills or incinerators[19]. Moreover, recycled plastics typically endure only a few recycling cycles[3], with approximately 10% undergoing multiple rounds[31], and are often mixed with virgin materials to maintain the desired properties[24].

About 90% of plastics production relies on oil and gas feedstocks[23], and in 2019, this accounted for 6% of the world's oil production used as raw material[32,33]. The surge in fossil fuel availability for plastic production, driven by global decarbonization efforts in the energy and transport sector, exacerbates the issue. Recent developments in creating alternative materials like bio PET and bio PE aim to promote reduction of fossil resource use and to reduce life cycle CO_2 emissions. Incorporating these bioplastics, identical to their fossil fuel versions, into existing recycling methods, however, remains crucial to their positive impact and avoid waste problems and plastic pollution at EoL[34]. The readily available and inexpensive fossil fuels present a significant disincentive to building waste collection infrastructure, particularly in low income countries where funding and planning are already insufficient. This poses substantial challenges to enhancing recycling efforts and developing a more robust waste management system[4,35].

Consequently, the low recycling rate leads to a disparity between the demand and supply of recycled plastic resins[36]. Additionally, market values of reprocessed resins are compromised by their reduced structural integrity. Advanced techniques, such as solid state polymerization, offer solutions by enhancing polymer chain reassembly and strength by heating the polymer without reaching melting points. Often contaminated plastic waste from industries or agriculture chemical packaging limits the application of recycled products[1]. The ambition to incorporate more recycled plastics into products confronts the reality of the shortage of high quality and volume plastic waste and reprocessed resins[37]. Regardless embracing plastic recy cling, has the potential to generate substantial profits of up to USD$60 billion by 2030, within the petrochemicals and plastics sector[37]. However, utilizing recyclates as direct replacements for virgin plastics is crucial to undercut the production of the latter and to prevent the proliferation of low end, disposable goods. A strategic shift in the market towards high quality recyclable materials is essential for bridging the existing gap in the recycling ecosystem and for the realization of the sector's financial potential.

Among other challenges to the unique composition of every plastic and availability of cheap virgin plastics, the lack of consistency and standardi zation in waste handling approaches are major obstacles across the globe. The Resin Identification Code (RIC), is defined for polymers under the 1 6 category, while category 7 includes all others[7], with no dedicated class for nonrecyclable, biodegradable polymers such as polylactic acid, and elasto mers including rubbers. Since the inception of RIC in 1988, the progress in polymer science has added several plastics into the market, emphasizing the need for a comprehensive tagging system including factors like colour for better material recycling. Similarly, certifications and permits associated with labelling should be updated to reflect modern scientific understanding and findings. Additionally, eco labels, such as those indicating biodegradability, plastic free, or eco friendly, issued by third party certifiers assist the plastic recycling ecosystem. For example, the label (green dot) introduced under the producer responsibility for plastic packaging products in Germany boosted the recovery of recyclable plastics[6]. In contrast, the positive impact can remain unrealized when the product features generic and self declared misleading claims to greenwash and confuse consumer decision making[38]. For example, "100% Recyclable" (Coca Cola and Nestle)[39], "Degradable" (Coco Thumb), and "Microplastics Free" (Wital tea) without scientific merit to attract green purchases amplify the gravity of the situation.

Environmental impacts of recycling

The use of plastic is anticipated to triple by 2060 compared to 2019, driven by the expanding global economy; however, the recycling rate may double during this period, creating a significant unintended environmental leakage[2,40]. Until now, the environment has been housing multiple layers of first generation nonbiodegradable plastics that have transgressed different compartments[4], which may unfold as a catastrophic environmental chal lenge. It is estimated that 19 23 Mt of plastic waste generated globally in 2016 entered aquatic ecosystems, but could reach up to 53 Mt annually by 2030[3]. Legacy plastic pollution is not just limited to marine and aquatic ecosystems. Due to the widespread use of plastics in agriculture and their limited recyclability, an estimated 12.5 Mt of plastics accumulate in agricultural soils annually[1,41]. Additionally, recycling alone cannot reverse the damage incurred due to the leakage of plastics already in the environment[21,35].

Plastic recycling encompasses both positive and negative aspects, warranting a comprehensive evaluation to balance environmental benefits and burdens. Recycling plastic waste significantly reduces fossil fuel utili zation, power consumption, and landfilling[30,42]. The ripple effect is a decline in the emission of greenhouse gases, thus lowering the carbon footprints while contributing to the global economy and direct jobs. In fact, it is emphasized that reprocessing 1 ton of plastic can save up to approximately 130 million kilojoules of energy[24]. A life cycle assessment (LCA) conducted on the environmental impact of 1) recycling plastic waste compared to alternative approaches and 2) application of secondary products instead of virgin materials marks a positive step toward climate control[30]. Similarly, several other LCA studies have confirmed the superiority of plastics as material over their alternative option such as aluminium bottles, paper, and cotton bags[43,44]. However, a notable limitation in several standard LCA methodologies lies in omitting a crucial factor the long term fate of che micals and particulates released during EoL plastic[1,45]. The disadvantage of existing short term LCAs in disregarding the consequences of chemical and particulate releases raises concerns about the overall efficacy of plastics and recycling as a solution to plastic pollution. This gap in evaluating the true ecological footprint of virgin and recyclate plastics (i.e., raw materials transported to a waste recycling facility for processing into a new materials or products) may result in unintended environmental and health costs.

Recycling facilities have been identified as potential hotspots and contributors of toxic and hazardous waste, however, there is limited attention to chemical or particle release from plastic recycling facilities. Despite the current and emerging technologies to recycle plastic waste, non recoverable tiny plastic particles (microplastics) cannot be addressed with existing col lection methods due to their exceptionally small size. Further, the size reduction and washing during mechanical recycling facilities tend to release significant microplastics into the environment[46]. About 13% of plastics infiltrate water or air as microplastics from recycling facilities in the UK[47]. A study on PET recycling facilities reveals microplastic releases range from approximately 23 1836 mg/L in wastewater that is distributed in the effluent (8 83 mg/L) and the sludge (52,166 68,866 mg/L) as it leaves the facility[48]. Microplastics generated during the recycling process are governed by the properties of plastics (polymer type or hardness) and environmental exposure[46]. Ideally, plastic recycling facilities are equipped with filters to prevent and mitigate environmental contamination, but it partially mitigates microplastic release and is not a comprehensive solution[47]. Additionally, the leaching of harmful plastic chemicals during and after recycling also poses a significant threat[29]. Recycled plastics exhibit higher levels of hazardous chemicals such as brominated flame retardants as legacy contaminants. The contamination not only hinders the wide application, it also poses health risks for workers and end users[12]. With this, it is imperative to produce toxic chemical free material through controls over what is being recycled and standards for recycled plastics and their usability in different sectors.

While chemical recycling can produce food grade plastics and has been heralded to fix plastics recycling, it is financially risky and can have far reaching environmental implications compared to virgin plastics production[8,21]. The damage to the environment through chemical recycling in terms of emissions, energy consumption, and water utilization surpasses those used in other technologies[49]. Meanwhile, mechanical recycling is believed to exhibit a lower overall impact on climate change than chemical recycling and energy recovery, which contributes to greenhouse gas emissions and photochemical ozone formation[42]. To address these concerns effectively, the transport and sorting of waste should be confined within closed spaces, filters should be installed and wastewater should be treated to prohibit the release of plastics and associated chemicals into the environment[36,50]. Despite an apparent increase in the plastic recycling rate, lower grade polymers with a limited lifespan are eventually disposed of as waste, thus challenging the circular economy of plastics and environmental sustainability.

Inefficient waste collection, coupled with the necessity for sorting before recycling, requires transportation to dedicated waste handling facilities leading to inadvertent loss and an escalation in carbon footprints. However, the global plastic waste trade is built on the premise of exporting for recycling, often to lower income countries[51]. Countries are also fraught with widespread environmental impacts and incredibly low recycling rates if accurately reported[52]. Further, regional policies have far reaching effects on global plastics recycling dynamics. Until 2018, China had been the repro cessing house for more than 50% of PET bottles[53], but the recent ban on foreign waste imports, including plastics, has left world recycling facilities scrambling[54]. High income countries began exporting plastic waste to other low income countries, particularly those in the global south[51,55]. Many of these low income countries have become disproportionally impacted by plastic pollution due to overwhelming imports of plastic waste (for so called "recycling"), as part of the global plastic waste trade[52]. These countries lack adequate recycling facilities, which has led to excessive open dumping or burning of plastic waste, including waste to energy incineration[35,51]. Imported plastic, often of low quality, contaminated, or mislabelled, is diverted to landfilling and incineration, each contributing to negative environmental impacts. The other example of change in plastic waste dynamics includes the largest exporter of plastics (i.e , Japan), which saw a surge in reprocessing, while the use of virgin plastics increased in China which further increased the carbon footprint following the import ban[56].

Achieving plastic circularity and plastic recycling in the Global Plastics Treaty

Currently, we are in the midst of a global plastic pollution problem driven by unsustainable plastic production and plastic consumption[20]. The plastics industry narrative has previously been framed around the unique recycl ability of many plastic polymers, but the reality is that plastics have been grossly mismanaged[3,57]. While recycling plays a role in managing plastic waste, doubts linger if it is a holistic solution[21]. The combination of poor polymer and product design, the nature of mixed waste generated, inade quate and wide variations of waste management infrastructure, poor quality of post recycling products, demand supply gaps, and environmental, eco nomic, and social impacts have resulted in unsustainable plastic waste generation[7,19]. With technological limitations and substandard industrial compliance, plastic recycling is not working. Globally, the recycling rates for plastic are paling in comparison to paper and metals, with a high recycling rate of aluminium at 76%[58]. Even if plastics are recycled, the environmental impacts are startling, particularly with chemical recycling[42].

Addressing the challenge of reducing global plastic production is complex, particularly given the disparity in plastic consumption between developing and developed economies. With almost 4 billion people residing in developing countries utilizing considerably less plastic than their coun terparts in developed nations, there exists a growing trend towards increased production and usage in these regions. Further, the global trade in plastic waste often involves shipping to countries with lower processing costs. The extended producer responsibility (EPR) schemes have the potential to internalize the environmental costs of production and waste management, providing incentives to reduce the use of virgin plastics and improve the quality of recyclables[59].

The transformative shift to global plastic sustainability demands a 50% reduction in future plastic demand, coupled with phasing out of fossil derived plastics, a remarkable 95% recycling rate for retrievable plastics, and a tran sition to renewable energy sources to establish a sustainable circular plastics economy[60]. Although current technology for plastic recycling is yet not cir cular, robust steps in tandem with changing regulations and research efforts are needed to encourage a decline in the impact of plastics. The time lag to achieve a complete closed loop recycling for all plastic produced accentuates the need to cap production and explore design for recyclability, extending beyond mere reducing and reusing these materials. Bridging the gap between escalating plastic production and effective recycling demands substantial immediate investment in research and infrastructure to maintain the plastic waste within the value chain without resorting to down cycling or disposal.

Achieving sustainability and a circular economy requires recognizing the importance of methods beyond recycling, including product design, alternative materials, phasing out problematic plastics, curbing the con sumption of virgin plastic materials, and adopting reduction and reuse strategies[23] (Fig. 1). The paradigm shift necessitates a decoupling from fossil fuel reliance and embracing recycled and biobased feedstock, towards CO_2 emission neutrality. Importantly, the focus extends to EoL considerations, where plastics should either be efficiently collected and economically recycled or designed to be completely biodegradable if dispersion is unavoidable[61,62]. Crucially, future polymer designs should not only meet traditional performance and cost but also incorporate safe and sustainable by design principles. A simplified plastic with a design for recyclability along with controlled chemicals, labels, and adhesive in finished products has the potential to encourage recycling rate[11,50]. Embracing a mono material approach in product design, where single polymers are utilized without compromising performance, and innovative solutions such as debonding on demand techniques offer pathways to address the challenges posed by multilayer plastics products[61]. Additionally, establishing standards and global policies is crucial to capping plastic production and curbing the continuous flow of plastic waste into the environment[63].

The reaction to the looming global threat of irreversible plastic pollu tion is through decreasing plastic emissions[64]. Life cycle analyses indicate net zero emission plastics are achievable using current technology, through a synergistic approach that integrates biomass, CO_2 utilization, and attains a 70% effective recycling rate, which significantly reduces energy use and operational costs[65]. Further, addressing the global plastic waste crisis requires the implementation of internationally coordinated waste man agement strategies[64]. Countries are implementing economic instruments to stimulate plastic recycling via different methods under the polluter pays principle including EPR[66], deposit refund schemes (DRS), tax on virgin plastics, landfill and incineration taxes, and pay as you throw schemes[67,68]. For instance, DRS, a lucrative refund incentive once applied to glass bottles, successfully promotes collection and reduces plastic littering. DRS accu mulates less contaminated plastics over the traditional single stream recy cling process. The scheme has incentivized as high as 95% of plastic bottle recycling in Norway whereas Ecuador reported an 80% collection of PET bottles in 2012 as compared to 30% in 2011[69]. Similarly, in 2019 plastic collection under DRS has increased in different countries including Den mark (94%), Croatia (89%), Estonia (87%), and Finland (90%)[69].

The challenge of EoL plastic has been recognized by the international community with 175 United Nations member countries agreeing to elim inate plastic pollution with a legally binding plastic treaty instrument[70]. The international community with the ongoing Plastics Treaty negotiations have already established a zero draft document and an updated revised zero draft document, which includes elements to address inadequacies of current plastic recycling[50]. Those include primary plastic polymers, chemicals, and polymers of concern when recycling complex mixtures of plastic waste[71]. Additionally, problematic and avoidable single use plastic products will be included in the Global Plastics Treaty as these are invariably difficult or impossible to recycle and should be phased out or replaced with sustainable alternatives[72 74]. Sustainable product design, performance, and practices such as reduction, reuse, refill, and repair will be emphasized.

Another important element of the Global Plastics Treaty includes the use of increased recycled plastic contents amidst the challenge of rising global plastic production, largely from virgin plastics[21]. To increase recycled plastic contents as part of the Global Plastics Treaty, governments could implement economic policy instruments to incentivise the price of recycled plastics compared to virgin plastics. For example, industries utilizing recycled plastics could be offered lower corporate taxes, whereas industries using virgin plastics would incur penalties (higher corporate taxes). The transition to a circular economy needs to reduce resource consumption and plastic pollution by moving away from the current linear economic model of plastic production[63]. Only focus on improved recycling and improvements in waste management facilities will promote increased production of waste as it will not cap production and will effectively lock in the global community to business as usual.

Finally, the Global Plastics Treaty will also include elements of EPR, emissions and releases of plastic through its entire life cycle, transformational improvements to waste management, as well as a just transition for waste pickers who play a major role in driving the informal recycling sector in many jurisdictions. Overall, it will offer opportunities to improve plastic recycling and eliminate harmful chemicals used in plastic production, manufacture, and packaging.

Concluding remarks

An immense variety of plastic products comprising a complex mixture are used in every aspect of modern society. However, the sustainability of these invaluable materials has largely been ignored. A staggering 91% of plastic meets an alternate fate than recycling. To improve the sustainability of plastic recycling we need a coordinated global panacea of solutions, as there is no one silver bullet to solve the pervasive plastic pollution problem. Emerging recycling technologies will help contribute to the panacea of solutions, but without global coordination, such as the Global Plastics Treaty, they alone will not address the plastic pollution crisis until it is controlled at the source with plastic production caps. Under the Global Plastics Treaty, United Nations member countries could consider adjusting the international price of virgin plastics to reflect the true environmental and economic costs of plastic pollution on ecological and human health. Reducing global virgin plastic production and overall consumption will help the implementation of an effective Global Plastics Treaty that will comprise comprehensive elements to reduce plastic pollution and increase plastic recycling to achieve a circular economy.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

N.S.: Conceptualization, Methodology, Discussion, Funding acquisition, Writing-original draft, review & editing. T.R.W.: Conceptualization, Methodology, Discussion, Funding acquisition, Writing-review & editing. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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Appendix C

Environmental and Social Incidents in Plastics Refining and Recycling

Southeast Asia

- Formosa Plastics, Vietnam (2016): toxic waste release resulting in large scale fish die-off, affecting local economies and marine ecosystems.
  - **Environmental Harm Scale – High**: long-term marine impact and community displacement
- Veolia, Thailand: Reports of water pollution from wastewater discharge containing microplastics.
  - **Environmental Harm Scale – Moderate**: localized water contamination, risk to marine life.
- X-Press Pearl Incident (Sri Lanka, 2021): In May 2021, the X-Press Pearl, a cargo ship carrying chemicals and plastic pellets, caught fire and sank off the coast of Sri Lanka. The incident released a vast amount of plastic pellets into the ocean, causing extensive environmental damage along the coastline and affecting local fisheries.
  - Company Responsibility and Legal Action: The ship was operated by X-Press Feeders, and the incident led to international criticism regarding the transportation of plastic pellets. Sri Lanka filed a $40 million interim claim against X-Press Feeders to cover the environmental damage, though the case is ongoing.
  - Environmental Impact and Damages: The United Nations classified the incident as one of the worst maritime disasters, as the release of pellets harmed marine life and fisheries along the Sri Lankan coast.

United States

- ExxonMobil, Texas: Regular air quality violations reported, including releases of benzene and VOCs.
  - **Environmental Harm Scale - Moderate to High**: localized health issues, potential for groundwater contamination.
- CarbonLite, California: Fire incidents and air quality concerns related to plastic dust.
  - **Environmental Harm Scale - Moderate:** air pollution, worker safety issues.
- Formosa Plastics (Texas, USA): In 2019, Formosa Plastics was implicated in a major plastic pellet spill into Texas waterways, affecting Lavaca Bay. The company faced accusations of illegally discharging millions of plastic pellets (nurdles) and powder into the water over several years.
  - Legal Action and Outcome: In 2019, Formosa Plastics settled a $50 million lawsuit filed by local environmental groups under the Clean Water Act. This lawsuit, one of the largest environmental settlements of its kind, mandated Formosa to improve containment and cleanup practices. The settlement also required the company to conduct extensive environmental monitoring and fund community-based environmental projects.
  - Fines and Damages: The $50 million was allocated toward environmental restoration and community compensation for the damage caused by the spills. This lawsuit set a legal

precedent in the United States for holding plastic manufacturers accountable for pellet pollution.

- Formosa Plastics (Louisiana, USA): Formosa Plastics also faced scrutiny for emissions of hazardous air pollutants, including VOCs, at its Louisiana facility. Local residents and environmental organizations raised concerns about increased cancer rates linked to air pollution from the facility.
  - Prosecution and Civil Claims: In 2020, a coalition of environmental groups filed a civil lawsuit under the Clean Air Act, which led to the EPA investigating emissions at Formosa's Louisiana plant. No fines were issued in this instance, but the company faced heightened oversight, and community protests have continued, leading to delays in expansion plans for new plastic manufacturing facilities in the region.
  - Regulatory Impact: Local and federal agencies, including the EPA, increased monitoring of Formosa's emissions, placing pressure on the company to implement air quality improvements to avoid future fines.
- Westlake Chemical (Louisiana, USA): Westlake Chemical was fined for multiple air quality violations related to VOC emissions and benzene leaks from its plastic manufacturing facilities.
  - Legal Action and Fines: Westlake faced fines from the EPA, including a $2.2 million penalty in 2021 for violations of the Clean Air Act. The EPA and the Louisiana Department of Environmental Quality (LDEQ) ordered the company to upgrade its pollution controls to reduce VOC and benzene emissions.
  - Outcome: The penalties also required Westlake to invest in facility upgrades and additional air quality monitoring, aiming to limit emissions and reduce health risks for nearby communities.
- ExxonMobil (USA and Asia): ExxonMobil, one of the largest producers of polyethylene and polypropylene resins, has faced criticism for its carbon emissions, with significant contributions from its plastic manufacturing operations.
  - Prosecution and Claims: In 2021, several U.S. states and environmental groups filed lawsuits against ExxonMobil, alleging misleading environmental claims, known as "greenwashing," related to the impact of its plastic and fossil fuel production. These cases are ongoing, with plaintiffs seeking damages and accountability for climate-related impacts.
  - Fines and Penalties: While ExxonMobil has faced various environmental fines over the years, none were specifically tied to plastic resin manufacturing. However, the cumulative legal pressure has led Exxon to invest in emissions reduction initiatives, including carbon capture and recycling research.

Europe

- BASF, Ludwigshafen: Accidental chemical releases and explosion in 2016.
  - **Environmental Harm Scale – High**: worker casualties, localized air and soil contamination.
- Veolia, France: Wastewater issues with microplastics leaching into local waterways.
  - **Environmental Harm Scale - Moderate to High**: (risk to ecosystems, regulatory fines).