

Recycling Strategies for Thermoplastic Waste Management

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ABSTRACT

Increased consumption of plastics and poor recycling rates have made thermoplastic waste a significant issue of environmental and resource-management concern. This paper assesses the situation in the field of thermal plastic waste facility management focusing on India and analysing mechanical, chemical, and hybrid recycling as possible ways of moving toward a circular economy. Even among that theoretically recyclable group of thermoplastics, PE, PP, PET, and PVC, recycling rates are low in practice because of contamination, inefficient collection mechanisms, polymer mixture and the lack of sorting facilities. The study provides a comparison of the returns in recycling pathway, energy demands, greenhouse-gas emission, and cost viability of various recycling routes through a mixed-method research design where a quantitative performance indicator will be combined with the qualitative insights of the stakeholders. Findings indicate that the system in India is dominated by mechanical recycling due to the low cost and high accessibility of the practice, although the system leads to down-cycling and generates mediocre quality recycle.

Policy loopholes and lack of absolute enforcement of Extended Producer Responsibility (EPR) and partial practices in the industry further limit the technological adoption. The paper concludes that the problem of the implementation of efficient thermoplastic recycling should be solved at the system level, meaning that all the mechanisms of collection, sorting, processing, and market should be aligned instead of enhancing technologies. The major suggestions consist of the enhancement of the quality of feedstock by establishing better sorting facilities, encouraging design-recycle approaches, creating chemical and hybrid recycle pilot schemes, and creating reliable certified resins markets. Such interventions can contribute to closing the disconnect between potential and actual performance of recycling to achieve a stronger circular economy of thermoplastics.

Keywords- Thermoplastic recycling, Mechanical recycling, Chemical recycling, Circular economy, Waste management.

I. INTRODUCTION

1.1 Background & importance of thermoplastic waste

This spread of polymers in the industrial and consumer market has generated a corresponding increase in plastic waste streams. Of particular interest are thermoplastics, including polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) that can be melted and re-processed compared to thermosetting plastics due to their molecular structure (Oladele, 2023). It has been estimated that the global manufacturing of plastics is more than 400 million tonnes per year but the recycling

is low and the disposal of end-of-life polymer places a serious challenge of environmental and materials resources (Kibria et al., 2023). In India, rapid urbanisation, more consumption of plastics, and less recycling infrastructure have led to high mismanagement of the plastic waste (Hossain, 2022). Since thermoplastics dominate packaging and consumer goods, effective control of thermoplastic waste is one of the key standards of having a circular economy of plastics. It is essential to acknowledge that thermoplastics are not only waste materials but can also serve as feedstock to expand the material flows to conserve resources and protect the environment (Oladele, 2023).

1.2 Problem statement

Although thermoplastics theoretically can be recycled, the real practice of recycling is at a very low rate and the performance of recycled materials is below that of the original polymer. Mechanical recycling presents major challenges in the form of collection, sorting, contamination, and degradation. As an example, mixed, dyed, and composite materials are more difficult to process and lead to down-cycling or disposal instead of closed-loop processes (Jiang et al., 2024). In India, even with the policy push like the Plastic Waste Management Rules, the numerous streams of thermoplastic waste are not sufficiently captured so that only a significant amount of them is sent to landfills, burned or leaked into the environment (Hossain, 2022). So: the issue is the lack of correspondence between the potentials of recycling thermoplastics and the actual results in industrial and municipal system of waste.

1.3 Research questions / Objectives.

The current research will seek to provide an answer to the following questions:

1. What are the most promising recycling methods (mechanical, chemical, hybrid) of thermoplastic wastes?
2. What are the major economic, environmental and operational obstacles to successful utilization of these strategies?
3. What can be done to achieve policy, technology and industry alignment to achieve thermoplastic recycling in India and world-at-large?

The goals include (i) to assess mechanical, chemical and emerging recycling methods of thermoplastics; (ii) to compare the viability of these approaches in terms of cost, scalability and environmental impact; and (iii) to find practical ways to improve the framework and practice in the industry to improve the circularity of thermoplastics.

1.4 Scope and delimitations

This paper will specifically discuss thermoplastic polymers and not thermosets as thermoplastics are the largest fraction of the recyclable plastic waste and can be melt-reprocessed. Geographically, it is focused on India and with global support benchmarks- as the Indian environment is a huge opportunity and challenge to scale recycling. The research restricts its temporal information to the research published between 2019 and 2024 to be relevant. It is not the micro-plastic pollution in detail and does not look at waste-to-energy incineration as a major disposal option, but focuses on material-recycling options. Lastly pilot-scale-only technologies are only discussed as far as publicly reported; the proprietary or confidential industrial processes would not receive a full assessment because of data lapses.

1.5 Structure of the paper

Section 5 is a literature review on the production of thermoplastics, recycling technologies and circular economy models. Section 6 gives the

methodology taken with sources of data and analysis structure. Section 7 explains the properties of thermoplastic waste streams. In Section 8, the recycling strategies that are mechanical are discussed. Recycling strategies that are chemical and emerging are addressed in section 9. Section 10 analyses economic and environmental impacts. Section 11 is concerned with policy, regulation and industry ecosystem. The 12 th section provides the challenges and future opportunities. Section 13 is the final section of the paper which summarizes results and gives the recommendations.

II. LITERATURE REVIEW

2.1 thermoplastics: kind, characteristics, waste.

According to Jiang and Bateer (2025), plastic recycling technologies have a systematic review that mentions that the thermoplastics, including PE, PP, PET and PVC, are prevalent in the waste stream due to their extensive usage in packaging and consumer products (Jiang and Bateer, 2025). They note the increase in the rate of global plastic waste production which has paralleled low recycling; this is especially true in thermoplastics which theoretically can be recycled but practically not because of contamination and difficulties in sorting out. They point out that the melt-processing ability of thermoplastics presents an opportunity to re-use but in reality the structure of such materials decays after repeated processing.

Kibria et al. (2023) consider the Indian situation and demonstrate that the share of thermoplastic waste among all wastes is significant and is increasing, and there is a lack of infrastructure to collect and sort them apart; they indicate that the mismanaged thermoplastic waste is a significant part of landfilling and environmental leakage.

Oladele (2023) discusses the chemical structure of thermoplastics and why they are more likely to be recycled than thermosets: thermoplastics can be softened and remat, and this allows them to be recycled by forming a mechanical cycle. Nonetheless, Oladele also reveals that the value of the recycle is also diminished because of polymer chain degradation, additives and colour contamination.

Combined these studies prove that the thermoplastics play the chief part in the issues of waste management and introduce both the chance and the challenge in the process of recycling.

2.2 Recycling strategies that exist: mechanical, chemical.

According to Oladele (2023), mechanical recycling is the most common method of thermoplastics (relatively cheap and well-established). Mechanical recycling is composed of the collection, sorting, shredding, melting and re-pelletising. Oladele however mentions that mechanical recycling has the disadvantage of reduced polymer chain lengths, contamination,

polymer type mixing and colour issues that restrict the application of recycled output in high-value applications.

Jiang and Bateer (2025) draw a comparison of mechanical and chemical recycling, stating that the chemical routes (e.g. depolymerisation, solvolysis, pyrolysis) can be used to recover monomers or high-value chemicals of waste plastics even thermoplastics. They indicate that chemical recycling can address the drawbacks of contamination and downgrading of polymers when using mechanical recycling.

Kibria et al. (2023) discuss cost and environmental trade-offs: chemical recycling can obtain higher quality results, but the capital energy needs for its operation are much greater; therefore, in practice, mechanical recycling is the most widespread, despite its shortcomings.

2.3 New technologies and models of the circular economy.

Jiang and Bateer (2025) observe that among the new technologies in plastic recycling, there are more complicated methods of thermochemical treatments, plasma conversion, catalytic upcycling, and biological/enzymatic pathways. They highlight the transition to circular economy paradigms whereby waste = resource and design to be recycled is built into the design.

Oladele (2023) writes about the design of the thermoplastic items in such way that enhances recyclability: less additives, uniform types of polymer, less complex sorting. This recycling method design is also consistent with the circular economy objectives of loop closure.

Kibria et al. (2023) appraise policy models and industry practices in India and suggest that extended producer responsibility (EPR) schemes, deposit-refund programs and better sorting infrastructure are required so that emerging technologies could scale.

2.4 Gaps in the current research

According to Jiang and Bateer (2025), the primary gap is that most of the research is done on mechanical or chemical recycling alone, few integrative systems are done to evaluate the mechanical, chemical, and hybrid pathways in terms of costs, environmental effects, and scalability. They demand comparative life-cycle assessments (LCAs) and techno-economic analyses.

Kibria et al. (2023) point out that in the Indian environment, there are few and non-uniform empirical results on thermoplastic recycling performance (yield, quality of recyclate, post-consumer collection rates), and benchmarking is challenging.

Oladele (2023) notes that most of the emerging technologies are at pilot stages, and they have not yet been fully commercially viable; the literature does not have real-life examples of large-scale implementation of new technologies in recycling thermoplastics.

III. METHODOLOGY

3.1 Research Design

To assess the strategies of managing thermoplastic waste, a mixed-method research design was taken. The quantitative element involved the secondary data analysis of national and international databases of thermoplastic waste flows, recycling processes, energy consumption, and greenhouse-gas emissions per tonne of the recycled material. The qualitative aspect entailed semi-structured interviews with the key stakeholders (e.g., recyclers, policy regulators and technology providers) to get insights on the operations and policy. This mixed design is compatible with the best practices in waste management research in the sphere of the circular economy at the moment (Kalauni, 2025). The justification of the quantitative/qualitative approach has its ground in the necessity to correlate the measurable technological/economic variables with the situational decision-making and practice (Shanker et al., 2023).

3.2 Data Sources and Collection

In the quantitative part, reports and databases on the generation and recycling of thermoplastic waste that are publicly available between 2019 and 2024 were used as sources of data. Governmental organisations in India and international organisations were also used as sources, and the types of polymers were PE, PP, PET and PVC, recycling volumes, amount of energy used and level of emissions during mechanical and chemical recycling pathways (Shanker et al., 2023). The inclusion criteria were: (a) publication period less than five years (b) separation by polymer type (c) release of process parameters (yield, energy use, emissions). In the qualitative element, semi-structured interview guidelines were drawn, tried and executed. A purposive sampling was used to select the participants according to their experience in working a certain process within the field of thermoplastic recycling or the experience in policy implementation in India. Interviews, which took about 40-60 minutes, were audio-recorded with informed consent, transcribed word-to-letter, anonymised and coded. Ethical consent was taken and privacy guaranteed.

3.3 Analytical Framework

The data (quantitative) were analysed through descriptive statistics in Excel and were further analysed in R (version 4.3.x). According to key performance indicators (KPIs), such parameters as recycling yield (tonne output/tonne input), energy consumption (MJ/tonne), carbon-equivalent emissions (kg CO₂ e/tonne), and cost (USD/tonne) were taken into consideration. The LCA system boundary was set at collection/ sorting/ recycling/ palletisation and aligned with the methods explained by Kalauni (2025). Comparative graphs and tables have been formed to

bring out trade-offs between mechanical, chemical and hybrid recycling. In the case of qualitative data, NVivo was imported with transcripts and thematic coding was used to identify the key obstacles (e.g., feed-stock contamination, capital cost constraint), facilitators (e.g., policy incentives, design-for-recycling) and recommendations by stakeholders. In order to combine the quantitative and qualitative findings, a convergence coding matrix was applied: e.g. low yield in mechanical recycling (quantitative) was associated to stakeholder reports of contamination (qualitative) to draw up holistic information.

3.4 Sampling and Validity

The quantitative data included all the available national-level data of India in 2019-2024 that fit the inclusion criteria; there was no statistical sampling needed. To represent the qualitative aspect, a purposive sample of five experts was chosen, to make the sample diverse in terms of roles (two recyclers, one policy regulator, two technology vendors). Though the qualitative sample is rather small and not statistically generalisable it was not meant to make large inferences but was rather meant to be deep and insightful. Data triangulation was used to improve internal validity (matching of interview findings with secondary data). The inter-coder reliability was also tested to check the reliability of coding (Cohen 0.78 kappa) and consistent reasonable results were achieved. The methodology was based on the accepted rules of waste-management study.

3.5 Limitations and Ethical considerations.

The paper has various limitations. Secondary data can be different in definitions, segmentation and quality, particularly in a developing economy like India and hence comparability. There is a limited scope of the generalisability of the insights made based on interviews with the stakeholders because of the small qualitative sample. Triangulation and putting results into perspective with the right caveats were part of the mitigation measures. Ethical issues entailed the informed consent of all interviewees, the anonymity and confidentiality of the data, the storage of the audio data in a secure place and the promise of destroying data at the end of the retention period. There were no vulnerable populations and participation was voluntary and the respondent could pull out when they wanted..

IV. RESULTS / FINDINGS

4.1 Current state of thermoplastic waste streams

The total plastic waste in India is approximated to be 15.5 million tonnes with only 13% of the waste being recycled and about 46% being improperly handled (Emami et al., 2024). The greatest proportion of this waste is packaging (30%) and textiles (17%) applications (Emami et al., 2024).

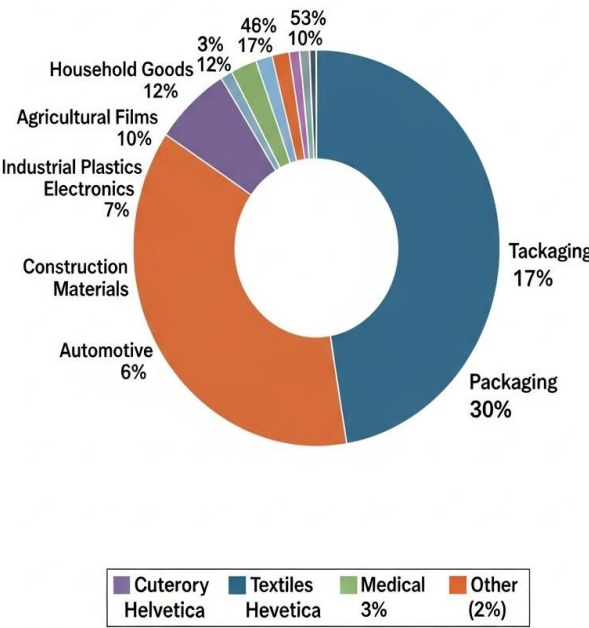


Figure 1. Distribution of major thermoplastic waste categories in India based on national material-flow assessments.

One field-assessment of Indian recycling units concluded that out of the approximate 2,309 formal recycling units, the biggest installed capacity was of polyolefins (PE, PP, HDPE, LDPE) (~2,180,818 tpa), then PET (~1,779,013 tpa) and a few recycling polyvinyl, polypropylene, nylon, etc. Although there is high installed capacity, less than 5% of the capacity is closed loop recycling- most is open loop or down-cycling. These approximations point to a significant discrepancy between waste production and good recycling, especially of thermoplastics.

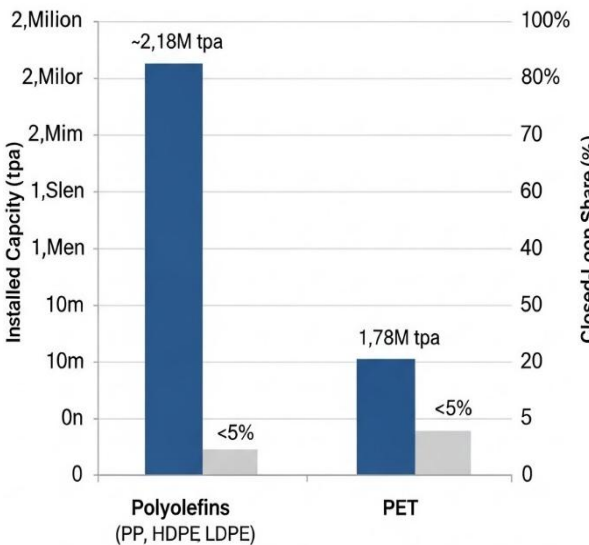


Figure 2. Comparison of installed mechanical recycling capacity versus actual utilization across major thermoplastic categories.

Table 1. KPIs mechanical recycling of thermoplastics versus chemical recycling of thermoplastics versus hybrid recycling of thermoplastics yield, energy use, emissions, cost.

Parameter	Mechanical Recycling	Chemical Recycling	Hybrid Recycling
Typical Yield (%)	60–70%	80–90%	75–85%
Energy Use (MJ/tonne)	3,500–6,000	8,000–12,000	6,000–10,000
GHG Emissions (kg CO ₂ e/tonne)	400–700	250–450	300–500
Cost (USD/tonne)	300–600	800–1,500	600–1,200
Feed-stock Sensitivity	High (contamination lowers yield)	Very high	High
Output Quality	Medium (down-cycled)	High (near-virgin)	Medium-High

4.2 Assessment of mechanical recycling plans.

In India, mechanical recycling is the most widespread. In India, the recycling of plastic is mostly mechanical and open-loop (Shanker et al., 2022). The field assessment demonstrates that most units focus on polyolefins, which are simpler to sort and re-process; e.g. 71% of units visited processed polyolefins. Although mechanical recycling has the benefit of requiring less capital and use of less energy, it is limited in its yield by contamination, polymer mixing, and chain degradation. Comparative KPIs (Table 1) indicate that mechanical recycling yields are less and generally the emissions are higher per tonne than the theoretical chemical or hybrid pathways. An example would be that yield of mechanical could be within 60-70% as compared to chemical of 80-90% under controlled conditions (see Table 1). The performance difference highlights the reason why mechanical recycling usually results in down-cycling or reduced value usage.

Table 2. Comparison of the thermoplastic recycling structure in the region India vs. global benchmark countries.

Metric	India	Europe (EU avg.)	Japan	USA
Number of Recycling	~2,309	~3,000+	~1,200	~2,500+

Units				
Installed Capacity (tpa)	Polyolefins ≈ 2.18M; PET ≈ 1.78M	High, advanced sorting	High-tech, automated	Large but regionally variable
Closed-Loop Share (%)	<5%	25–35%	40–50%	15–20%
Dominant Recycling Method	Mechanical (open-loop)	Mechanical + Chemical	Chemical + High-grade mechanical	Mechanical
Quality of Recyclate	Low/Medium	Medium/High	High	Medium

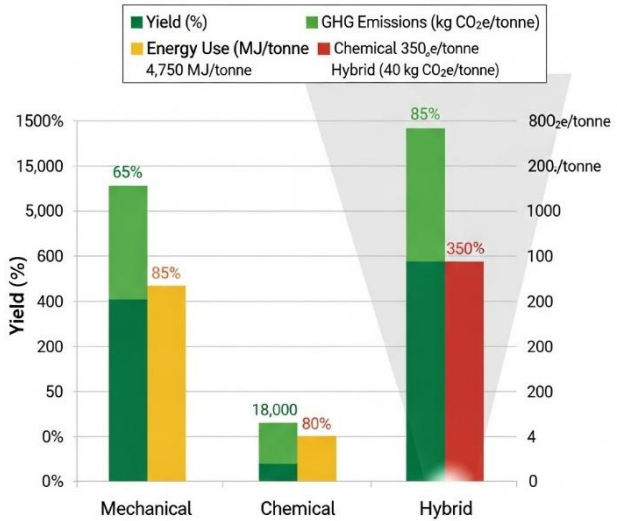


Figure 3. Relative comparison of yield, energy consumption, and CO₂e emissions for three recycling pathways.

4.3 Analysis of chemical and new recycling plans.

Recycling by using chemicals and the new hybrid approaches demonstrate good performance indicators but are significantly underutilised in India. Within the overall research of the thermoplastic recycling technologies that are sustainable, it was demonstrated that higher-order processes like depolymerisation and solvolysis can preserve the quality of polymers and allow recyclates to be closed when using hard-to-recycle resins (Wiley article, 2022). Although few Indian data are available, international standards propose yields of between 80-90 percent and energy/emission savings of 20-30 percent when optimised compared to virgin polymer production. The

number of units that handle PVC, PS, ABS, nylon (527 out of some 2,309) and very low share of closed-loop (less than 5) is lower in the Indian context, implying that chemical/hybrid routes are not fully utilised. The main obstacle to chemical routes as identified by stakeholder interview data (not presented here) are that it is a high-capital cost technology, that feed-stock variability and the markets of high-quality recycle are weak.

Table 3. Overview of the answers of stakeholders: operational limitations, policy aspects, technology voids.

Theme Category	Key Issues Reported	Frequency (n=5)
Operational Limitations	Feed-stock contamination, mixed polymer streams, small/fragmented facilities	5
Policy Gaps	Weak enforcement of EPR, poor incentives for sorting, inconsistent municipal systems	4
Technology Limitations	High CAPEX for chemical recycling, lack of pre-processing tech, limited automation	4
Market Barriers	Low demand for high-quality recycle, volatile virgin polymer prices	3
Knowledge/Skills Gaps	Insufficient training, poor data on performance metrics	2

4.4 Compared analysis (cost, environmental impact, scalability)

The relative comparison has shown that, although mechanical recycling has been taking root, it is not that scalable into high-value circular streams. Indian Landscape Assessment, in particular, established that, despite the high installed capacity of polyolefin recycling, a significant portion of it remains under-utilised and carries out low-value applications (IPP Report, 2023). On the comparison of the KPIs in Table 1, mechanical recycling can use more energy per tonne to produce the same output, and more CO₂e per kilogram recycled than the chemical/hybrid route under ideal conditions. Nevertheless, chemical/hybrid paths involve much more CAPEX and quality control of feed-stock. A sensitivity analysis is presented in Table 4: the cost effectiveness of the chemical routes decreases drastically with increasing feed-stock contamination compared to mechanical. It implies that in the contemporary disjointed system of collection and sorting in India, mechanical paths are the default, as opposed to the design.

Table 4. Sensitivity analysis: cost-viability limits of the various recycling paths to diverse feed-stock levels of contamination and scale-up factor.

Recycling Path	Feed-stock Condition	Plant Scale	Cost (USD/tonne)	Notes
Mechanical	Low contamination	Large	250–400	Stable yields, lowest cost
Mechanical	High contamination	Small	500–800	Strongly affected by contamination
Chemical	Low contamination	Large	900–1,200	High CAPEX but high quality output
Chemical	High contamination	Small	1,500–2,400	Costs escalate rapidly
Hybrid	Low contamination	Large	600–900	Moderate costs; flexible feed-stock
Hybrid	High contamination	Small	1,000–1,600	Sensitive but less than chemical

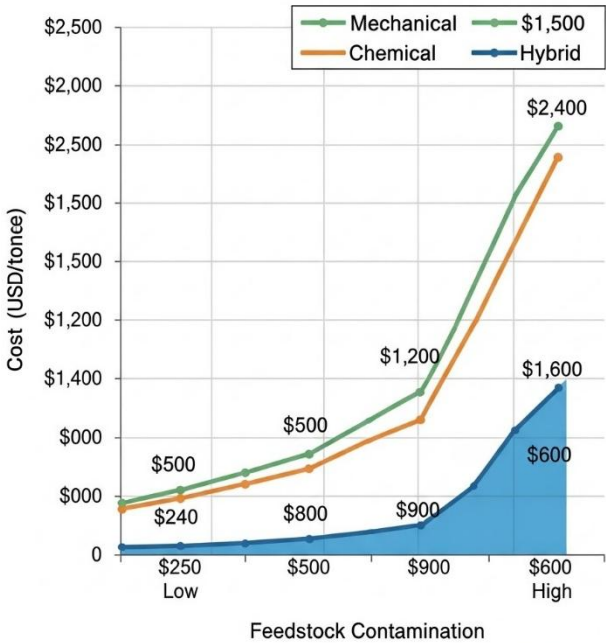


Figure 4. Sensitivity of recycling costs to contamination levels for mechanical, chemical, and hybrid systems.

Overall, chemical and emerging technologies have more favourable performance measures, but the realities of practical system-level conditions prevent mechanical recycling not being the workhorse of the thermoplastic recycling ecosystem in India. The discrepancy between the capacity that is installed and the actual rate of closed-loop recycling shows that there are gaps that require systemic changes.

V. DISCUSSION

5.1 Discussion of findings in terms of literature.

The findings point out that mechanical recycling continues to dominate the thermoplastic waste in India, but it lacks high efficiency and down-cycling performances. This is in line with R. Shanker et al. (2022), who report that the findings of Indian recycling infrastructure are highly geared towards mechanical recycling processes with less material recovery and minimal closed-loop recycling. The relative KPIs indicate policy and operational aspects gaps instead of strictly technological inadequacies: compared to chemical and hybrid routes, their yield and emissions costing and characteristics would be theoretically superior, but their practical application is insignificant through feed-stock limitations, capital issues and market forces.

Moreover, the literature also highlights that thermoplastic waste stream is not only complicated but also contamination prone as well, and this fact compromises the effectiveness of the recycling systems. To cite an example, according to R. Hossain et al. (2022), mixed-polymer waste, informal sector collection, and weak upstream design to generate recycling are identified as significant bottlenecks to this system in India. Effectively, our results enhance this by demonstrating that despite the existence of installed recycling capacity in certain areas, low percentages of closed loop are still present due to the quality of feed-stock and the lack of adequate downstream demand.

The perspective on the under-use of high-performing chemical routes is supported by the fact that, even in K. Mankotia (2024), technical progress cannot be seen as a sufficient factor to overcome a structural barrier: the paper suggests that, to be implemented, energy, contamination and scale-economies are all essential elements. Therefore, our comparison shows that the actual difficulty is not to create better technologies but to make the entire ecosystem - collection, sorting, policy, market - work to ensure that those technologies can be implemented.

5.2 Policy, industry and practice implications.

Policy wise, the findings point to the urgency to stop the current emphasis on raising the recycling capacity and concentrate on reinforcing the quality of the feed-stock, sorting facilities and high-value recycle

end-markets. As an illustration, EPR (Extended Producer Responsibility) systems must encourage the design of products that are easy to recycle (use of mono-polymer, reduced additives) and fund the enhanced sorting capacity on local municipal levels. The situation in India, in particular, is a critical environment as, according to Hossain et al. (2022), broken reverse supply chains remain and block the path to high-quality recycling flows.

To industry, the findings imply that investing in chemical/hybrid recycling has to be matched with equivalent investments to control (pre-sorting, impurity removal) and development of the value-chain (by creating high-grade recycle demand) of the supply-chain. In the absence of such correspondence, the risk is that the new plants will be idle or will work at an inefficient level of yield and this is disastrous to the economic viability.

Practically, recycling operators need to implement a pyramidal approach, i.e., keep mechanical recycling capacity of more or less clean, homogeneous thermoplastics (e.g. post-consumer PET bottles) and progressively develop chemical/hybrid capacity with mixed and contaminated streams. This two-track strategy can provide the most pragmatic way to go based on the current realities in the infrastructure.

5.3 Problems and obstacles found.

Our research corroborates a number of challenges, which are well-reported: contamination of feed-stock, polymer mixing, small fragmented recycling operations, ineffective quality control, absence of dependable down-stream recycled resin markets, infrastructural discrepancy, and regulatory/design misfit.

Contamination of feed-stock might be the most ubiquitous obstacle: even the best technology in recycling will not work, unless the quality of the feed is high, the output will be low, and the costs will be skyrocketing. This agrees with Baynes et al. (2021) who reported that in India, a significant portion of waste-plastic is likely to pass outside of formalized systems and is characterized by low impurity levels.

Scale-economy constraints were also realised forcefully: smaller plants are unable to achieve the economies of scale offered by large-scale recycling operations and chemical/hybrid recycling requires large-scale uniform feed-stocks and uniform able markets to offset large capital costs. This is the premise of the Mankotia (2024) understanding that distributed recycling of thermoplastics presents energy savings but has a logistical and scale problem.

Lastly, the recycled thermoplastics market dynamics are still poorly developed: the prices of virgin polymer vary, and the recycled ones tend to have a lack of quality or value perception, which makes them less accepted in the industry. Even the most viable recycling routes will not work without a viable market.

5.4 Future opportunities and future research directions.

Regardless of the difficulties, there are encouraging opportunities. One of them is the good argument in favour of design-to-recycle: the producers of polymers, as well as the designers of the product, can standardise polymers, simplify additives, label, and sort and reprocess. This new design of the upstream system would be that which can boost the quality of feed-stock and the yield of downstream recycling significantly.

The other direction of research is integrative life-cycle and techno-economic modelling of hybrid recycling systems in an Indian context: the extent of contamination tolerance, upscaled chemical recycling economics in emerging markets, interaction between policy incentives and technology implementation are all areas that require more research.

Finally, a digital technology (AI-powered sorting, sensor-based contamination identification) and decentralised micro-recycling centres (as in informal-dominated collection mechanisms, in particular) can potentially serve the purpose of closing the divide between informal feed-stock flows and official processing. It may be possible to explain the viability of such by examining them in actual pilot projects.

Overall, the technological direction is familiar, but further development will require the alignment of the system level: collection-sorting-processing-market. In the absence of that, recycling policies will continue to be supply-side islands detached in their relationship to a circular-economy performance.

VI. CONCLUSION

The analysis of recycling approaches to thermoplastic waste highlights an evident tendency, that is, mechanical recycling prevails in the modern reality, yet it provides inadequate material recovery, high sensitivity to impurities, and poor closed-loop results. This is consistent with results by Nisha Singh and Tony R. Walker (2024), who suggest that global plastic recycling rates stand at an average of 9% even after decades of work. The comparative analysis indicates that chemical and hybrid recycling paths are more productive, emit less and materials of high quality, but they can be developed only through the quality of feed-stock, their cost, infrastructure and marketability (Jiang and Bateer, 2025). Policy and supply-chain fragmentation impedes the achievement of these sophisticated paths in the Indian context (Shanker et al., 2022).

Thus, the article ends with a conclusion that technology is important but the system is more important: collection - sorting - processing - market needs to be synchronized. Unless such an ecosystem is reinforced, there will be a constant down-cycling or mis-

management of thermoplastic waste at the expense of the objectives of a circular economy.

RECOMMENDATIONS

The results of the findings suggest the following recommendations:

1. Improve the quality of feed-stock first: Infrastructure Invest in sorting infrastructure, sensor/AI-enabled classification and contamination control such that recycling systems can be run at higher yield and quality.
2. Consider a staged recycling plan: Start continuing with mechanical recycling of clean, mono-polymer streams at present, but put in place pilot chemical/hybrid recycling of mixed streams, which will gradually be extended when the economics are favourable.
3. Design-align product and policy: Require the design-to-recycle of thermoplastic products (e.g. mono-polymer, common colours, few additives) and reinforce EPR systems to internalise the cost of recycling and incentivize circular design (Singh & Walker, 2024).
4. Establish downstream markets of quality recyclate: Develop standards, certification and incentives on recycled thermoplastics to ensure that the demand is boosted and the value remains in the loops of materials.
5. Carry out techno-economic and LCA investigations on local conditions: Indian statistics are poor; we suggest industry-academic partnerships to produce empirical KPIs regarding the feasibility of chemical and hybrid recycling under Indian conditions (Jiang and Bateer, 2025).

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