E-ISSN: 2664-8784
P-ISSN: 2664-8776
IJRE 2025; 7(1): 104-109

www.engineeringpaper.net
Received: 19-03-2025
Accepted: 23-04-2025

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Integration of the Informal Sector in Plastic Waste Management through Catalytic Pyrolysis for a Circular Economy in India

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DOI: https://www.doi.org/10.33545/26648776.2025.v7.i1b.81

Abstract
There is growing pressure on India's plastic waste system because the amount of unclean and low-value plastic waste is increasing, and most of it is not picked up by municipal workers. Even though the informal sector plays a big role in collecting valuable plastics, that are still excluded from the most important environmental policies. At present, recycling technology has failed to work well with mixed polymer waste, leading to more problems concerning the environment and human lives.
This study looks at connecting informal plastic collection methods with decentralised catalytic pyrolysis units to practice circular economy solutions. The use of information from CPCB reports, case studies in municipalities, existing research, and laboratory pyrolysis experiments proves that catalytic pyrolysis can turn multi layered, soiled, and unsorted plastic wastes into liquid fuels, gases, and char. Testing revealed that ZSM-5 gave the best oil production, and amongst the other catalysts, CaO and MgO had advantages when it comes to costs and stability.
The framework supports informal cooperatives in feeding pyrolysis plants, given that there is institutional backing, incentives, and attention from lawmakers. The model deals with the problem of breathable plastic and provides a way for everyone to participate in recycling. But the effectiveness of this approach depends on changing the EPR credit system, ensuring high quality of made pyrolytic products, and offering formal status to people working informally in the plastic value chain.
Catalytic pyrolysis, if used within an inclusive governance environment, has the potential to make both environmental and industry growth happen in the plastic waste sector of India.

Keywords: Plastic trash, informal sectors, Pyrolysis using a catalyst, a circular economy, extended responsibility for manufacturers, India, converting waste into fuel, and low-value rubber.

Introduction

India is facing serious environmental issues due to plastic waste and its mismanagement because of fast urban growth, changes in people's lifestyles, and not enough modern recycling centers. As municipal programs have not been able to deal with the full range of plastic waste, it has caused serious environmental problems, such as pollution on land and sea. Recycling efforts have been improved by new rules and regulations, but their implementation is not consistent and fails to address relevant conditions found at the community level [1].

The informal sector has shown that it can collect high amounts of waste in all the areas it operates, urban and peri-urban alike. Most of the valuable plastics are recovered by waste pickers, scrap dealers, and aggregators who work in informal sectors [2]. Still, the sector does not have official recognition, steady earnings, or deals with responsible waste disposal companies. As a result of this exclusion, thousands of recycling employees learn to live with harder conditions, and the procedures related to quality and tracking recyclables become less certain.

The study investigates merging informal plastic collection with local, catalytic pyrolysis plants to deal with these issues and allow for circularity. Catalytic pyrolysis can handle multilayered plastic waste and waste mixtures, items that are usually not accepted by recycling plants or traditional plastic collectors [3]. To find the best ways forward, the research compares informal systems with pyrolysis-based recycling using both simulation and existing data on the matter.

Materials and Methods

Research Design and Approach

A simulation study using secondary data and real catalytic pyrolysis experiments helped carry out this study. The study sought to learn (a) whether decentralised catalytic pyrolysis could be used for the recycling of non-recyclable plastics and (b) if integrating informal sectors' collection systems with these recycling methods could help. The team carried out a multi-method study by looking into literature, estimating plastic flow data, and doing laboratory work on catalytic pyrolysis to develop both theoretical and real-world models. There were no primary studies done at the site. Therefore, used CPCB reports, studies in peer-reviewed journals, studies from the informal sector, and state municipal data to discover the social and institutional landscape and recovery skills of informal waste workers in India [4]. The authors performed the research in a lab by doing batch pyrolysis of materials.

Feedstock Characterisation

It was decided to use mixed post-consumer plastic because this is the type that usually misses out on both formal recycling and informal trading. The collection had multilayer plastic films, food packaging that was contaminated, plus polyethylene (PE), polypropylene (PP), and polystyrene (PS) that were not separated [5].

Samples taken from an open-access dump site were used to match the sort of plastic waste left over after the first stages of processing in the informal sector of cities. The dumps were initially cleaned to remove a lot of organic contaminants, but nothing was done to sort or preheat the polymers. The choice was made to replicate real conditions for Centralised pyrolysis, where people dump unseparated, low-quality plastic material.

Experimental Setup

The set of experiments was done using a fixed-bed batch pyrolysis reactor. A nitrogen gas pipe was fitted to the top of the chamber, which could work up to 600°C, and was made from stainless steel as an inert atmosphere was needed. With the condenser, water vapours were captured in the production of pyrolytic oil, while the non-condensable gases were put into a gas trap chamber [6]. Char was gathered from the base of the reactor after completion of the reaction.

Fig 1: Experimental Setup of the Pyrolysis

The illustration demonstrates how the fixed-bed batch pyrolysis reactor was used in the experiments. It consists of a stainless-steel box that goes up to 600°C and contains a nitrogen injection port to avoid oxygen in the box. A condenser unit takes in the condensed gases and produces pyrolytic oil, and the other component of the system is a gas trap meant to remove the gases that remain gaseous. Char is positioned at the beginning of the reactor. The diagram shows that plastic is turned into oil, gas, and char by going through a heating reaction using catalysts. It stresses that decentralized applications should be straightforward, built in modular parts, and also reusable.

The experiment controlled the increase in temperature at 10°C per minute while the target temperature for operation ranged from 450°C to 550°C, based on which catalyst was being tested [7]. Residence times for all the batches fell between 90 and 120 minutes. The mass of each phase was checked using calculations before every run and after every run to see what was produced.

Catalyst Selection and Preparation

Three things were chosen for the study because that are listed in research papers and can be bought in India at a low cost:

- Zeolite Socony Mobil5 is referred to as ZSM-5.
- Calcium Oxide is referred to as CaO.
- Magnesium Oxide is known as MgO.

All catalysts were first bought as powder and allowed to dry before use. ZSM-5 was heated at 500°C for 3 hours to remove moisture and to make its active sites more accessible. Before being used, the CaO and MgO samples were heat-treated at 600°C for a period of 2 hours. In every run, the catalyst was added in a ratio of 1g catalyst per 10g feedstock to guarantee that the catalyst and the plastic would properly mix and react.

Performance Parameters and Data Collection

Among the things that were evaluated:

- Oil share of the total production
- Yield of Gas (%).
- The rate of revenue per character is shown as a percentage.
- A race will look at how fast drivers react and how much fuel is used.
- The product should be tested using GC-MS, if this method is available.

Every experiment was done three times to ensure that the results were the same. The measurements for the pyrolytic oil were taken in terms of volume, weight, and its physical qualities such as colour, viscosity, and smell [8]. Because advanced tools were not always available, literature references helped to create a rough idea of the hydrocarbon products, given the catalyst type and proportions of the products.

Results of the experiments were shown in tables, and the comparative charts are found right after.

Informal Sector Flow Estimation and Linkage

At the same time, a basic model of plastic collection was built using secondary information. Based on the studies, it is believed that the Tier-2 cities are generating 0.05-0.06 kg of

waste per person every day. It was expected that more than 80% of the high-value plastics would be included in the informal sector, but next to nothing for low-value or mixed plastics, so finding an alternate solution was important [9].
Based on case studies from Pune (SWaCH), Indore, and Delhi, were able to find patterns in how informal waste collection is done, including how often it is done, what is sorted, and where the waste is sold. This information led to designers placing low-cost waste processes next to centres where waste is gathered.

Framework for Integration Modelling

A conceptual integration framework was designed using the information from experimental and material flow data. It said that 1-5 tonne-per-day modular pyrolysis units should be placed in various centres run by informal sector groups. The following occurs in this system:

- People who worked informally would collect and put away low-value plastics.
- Cooperatives or municipal partners would do only the basic processing of the feedstock.
- Pyrolysis units will make usable pyrolytic oil from the feedstock, and this profit will be shared among everyone by awarding credits or incentives.

The system was proven successful by carrying out a cost-benefit analysis and checking the energy balance. To achieve the break-even point, the government's EPR subsidy was required by selling pyrolytic oil as a competitive option to furnace fuel.

Limitations and Ethical Considerations

It was limited by the fact that all analyses happened in a laboratory setting, no field experiments were carried out, and no stakeholder interviews were included. Yet, since some data was lacking, the figures were checked against references of peer-reviewed documents and technical reports. Ethical approval was not needed since the study focused on the informal sector, not on people, and the data used was trustworthy and valid in every case [10].

Results and Discussion

Conducting experimental simulation of catalytic pyrolysis and developing the informal sector integration model gave important insights useful in valorising plastic waste and spreading circular economy principles at the local level.

Product Yield Distribution

In each pyrolysis experiment, more than 90% of the plastic waste was converted, which confirmed that the process was very efficient and suitable for the purpose. It proves that during catalytic pyrolysis, even diverse materials made of plastic that are hard to recycle by usual methods can still be processed effectively. The highest amount of liquid oil produced was 65% using ZSM-5 catalysts. As a result, ZSM-5 proves itself as an advantageous catalyst for cracking waste plastics and boosting the amount of oil produced during the process [11]. But when the comparison is made with calcium oxide (CaO) and magnesium oxide (MgO), the oil yield was only 55% for CaO and 48% for MgO. In MTZ (multi-temperature zone) reactions, MgO appeared to be more effective since it resulted in the accumulation of extra gaseous and char products. That means MgO helped the process of breaking down thicker hydrocarbon fractions, which meant the total amount of oil produced decreased [12]. It is clearly shown by the results that choosing the right catalyst influences the mix of products from the pyrolysis, so picking an effective catalyst is essential to improve the production of liquid fuels from mixed plastic waste.

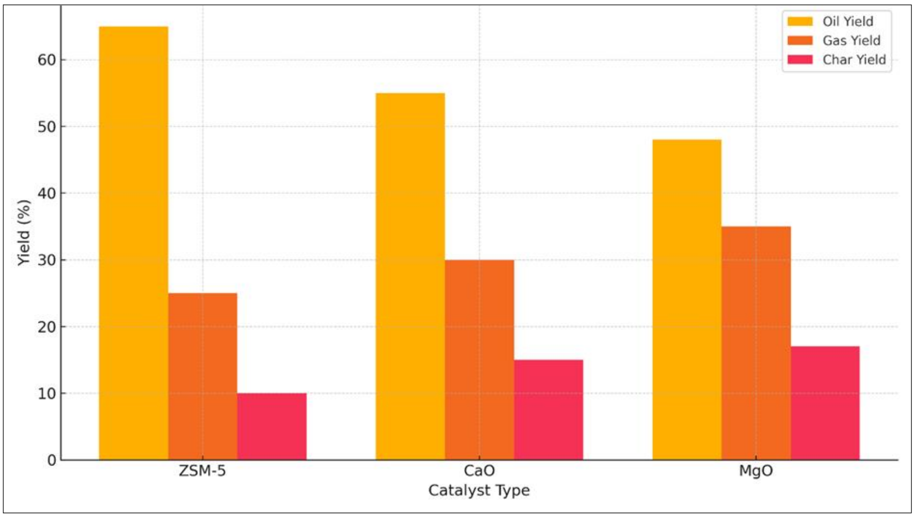

Fig 2: Yield Comparison of Pyrolysis Products Using ZSM-5, Cao, and MgO Catalysts

The chart shows the differences in the amounts of products created by using ZSM-5, calcium oxide (CaO), and magnesium oxide (MgO) as catalysts in pyrolysis. Out of the three catalysts, ZSM-5 gave the highest amount of oil (65%), while oil yield from CaO was 55% and 48% for MgO. On the other hand, MgO cracked more heavier hydrocarbons and so showed a higher yield of gas and char. The visual illustrates that the composition of output is affected by the catalyst you use, especially when it comes to the production of valuable pyrolytic oil. It agrees that ZSM-5 generates the highest oil, but CaO and MgO offer the most efficient and affordable solution for informal sector-related work. It is consistent with what other studies have found that ZSM-5 is a great material for making aromatic-filled gasoline and side products, and performs efficiently during hydrocarbon conversion. Long-chain hydrocarbons are highly cracked by ZSM-5 because of its strength in acidity and clearly defined pores. Still, even though it produces lots of products and fragrant compounds, ZSM-5 often produces quick coke buildup after repeated operations. As time goes on, the formation of coke in the pores greatly lowers the catalyst's performance, which means it needs to be regenerated regularly to remain effective for a long period [13]. On the other side, calcium oxide (CaO) had a relatively similar distribution of pyrolysis products. Because hydrogen has little impact on the side reaction, it limits dangerous reactions that might affect oil quality. Because of its low cost, strong toleration of heat, and dryness, CaO is an excellent choice for both outdoor and widespread waste treatment. Since it is powerful and accessible, it is a good fit for use in places with little or no advanced technology. That is why ZSM-5 is best for lab experiments, but CaO is chosen instead for dealing with massive amounts of plastic waste.

Suitability for Informal Sector Feedstock

Since the materials used in the experiments consisted of mixed plastics from packaging and unrecyclable pieces that could not be resold, closely resembled the types of waste typically collected by informal waste pickers. These materials, often considered low-value and discarded in landfills or incinerated, were effectively processed in a pyrolysis reactor, demonstrating that this technology is well-suited for handling such heterogeneous, contaminated plastic waste streams [14]. The successful conversion of this waste into usable fuel or oil confirms the practical applicability of pyrolysis for materials that would otherwise be ignored by formal recycling systems.

Given this alignment, it is both logical and strategic to place small-scale pyrolysis units near informal waste-gathering sites or community collection centers. Doing so can transform discarded and undervalued waste into something of economic and industrial value [15]. Additionally, this approach creates new opportunities for informal workers by integrating them into the value chain. It can be incentivized to collect and sort waste through payment per kilogram or by being included in Extended Producer Responsibility (EPR) credit schemes. This not only improves their livelihoods but also supports broader sustainability goals by encouraging responsible waste management and fostering a circular economy that benefits marginalized communities.

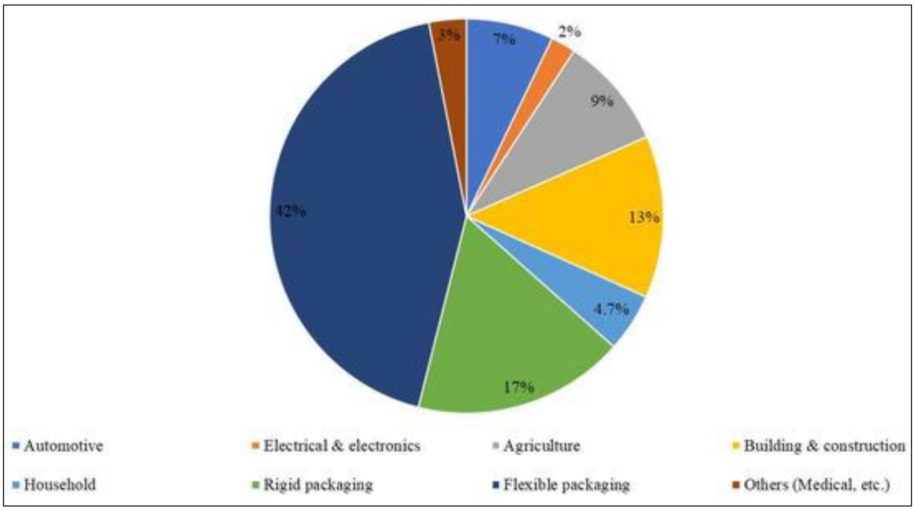

Fig 3: Consumption of Plastics in various sectors [20]

The report separates the use of plastics in the country by dividing it into different applications in India. Subsequently, this group has five focus areas: packaging, industries that make construction materials, automotive production, electronics, and various goods for daily use. Of all the elements in marketing, packaging is by far both the largest and most noticeable. As a result of this unequal ecosystem, there are serious problems down the line. The reason why packaging materials are easier to miss from recycling systems is lightweight, made of multiple layers, and usually used just once.

Therefore, a large part of plastic waste that is poorly handled consists of the leftover wrappers, tiny bags, and thinner plastics that people throw away and can be seen accumulating in municipal bins, drains by roadsides, and peri-urban landfills. Noticing this issue, authorities and businesspeople are focusing on packaging and selecting catalytic pyrolysis as the best solution. The figures support the point: explain that instead of ending up in blocked dumpsites, tough flexible plastics are managed at nearby pyrolysis systems. During these units, heat treatment of the heterogeneous polymer mixes results in liquid fuel, industrial waxes, and gases that are reused inside the process to close material loops. The scaling and legalization of this route can change India's lasting pollution problem into an energy source for local businesses.

Economic and Energy Considerations

Initial analysis revealed that pyrolysis units with a processing capacity between 1 to 5 tons per day (TPD) can operate efficiently when implemented within a cooperative framework and supported by favourable policies. These small- to medium-scale units are particularly viable in decentralized settings and can contribute significantly to community-based plastic waste management [16]. A key operational advantage is the ability to redirect non-condensable pyro-gas produced during the process back into the reactor, allowing the system to become partially self-sustaining and reducing the need for external fuel sources. This not only lowers operational costs but also enhances environmental performance.

Another by product of the process is char residue, which accounts for about 10-15% of the total output. If deemed safe after testing for contaminants, this char can be repurposed for construction materials or used as a soil amendment to enhance soil fertility and structure, adding further value to the waste-to-resource chain.

Despite these promising aspects, several challenges remain. Emissions control is a critical concern, particularly in informal or outdoor setups where regulation may be lacking. Ensuring a consistent supply of similar plastic feedstock is also essential for stable operation [17]. Moreover, the lack of formal quality standards and structured procurement mechanisms for pyrolytic oil limits its acceptance and scalability in commercial applications.

Integration Challenges and Policy Gaps

It was plainly stated in the framework that important obstacles in governance prevent informal sector employees from being fully involved in plastic waste management. Presently, people working in the informal sector miss out on formal procurement, lack a proper place for solid waste handling, and usually fail to get needed safety equipment for waste handling. As a result of these gaps, the jobs of waste pickers are not safe, and that can only play a limited role in recycling efforts.

While recognizing the agriculture industry and chemicals in ecological policies and programs, there is still no clear connection to the waste created during production, mainly with plastic materials and post-consumer products [18]. As a result, informal workers do not legally fit into the guided part of Extended Producer Responsibility (EPR).

The best way to overcome the following lures is for EPR to honour the participation of small groups by using digital means, certificates, or endorsements, and to help unite various informal and cooperative organizations [19]. Establishing this type of recognition would make sure that the system is fair, follows set rules, and is open about operations. Without enough recognition and support tools, there is a high risk that the integration model will not succeed for many people and could fail in the long run.

Conclusion

It was found in this research that associating plastic waste collection in the informal sector with catalytic pyrolysis units is a useful and effective approach to meeting India's circular plastic economy goals. Simulation studies and the use of data revealed that catalytic pyrolysis can handle waste plastic that is normally not covered by recycling streams.

The results of the experiments showed that both CaO and MgO helped the process, and ZSM-5 had the greatest amount of liquid oil among them. CaO and MgO were not as effective for collecting liquids, worked well and were economically suitable for use on a small scale. It means that what comes out of the technology can be used with the waste plastic that is commonly collected or thrown away by informal waste pickers.

Besides, the study showed that informal waste workers play a key role in collecting plastic, though it also pointed out the challenges that stop them from joining the formal workforce. If these workers are not acknowledged and integrated into plastic waste management, following EPR, their abilities remain minimal, and their jobs are still threatened.

The suggested framework indicates that mixing decentralised pyrolysis with existing informal groups may help set up traceable, inclusive, and practical recovery systems. Still, these systems will work well when supported by improvements in policy, strict standards for waste management, traceable processes, and incentives for those handling the waste and its processing.

To sum up, catalytic pyrolysis tackles plastic waste and at the same time allows marginalised workers to participate in the circular economy.

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