Compendium of Technologies for Plastic Waste Recycling and Processing

2021

Editorial Team

IGES Centre Collaborating with UNEP on Environmental Technologies (CCET): Kazunobu Onogawa and Dickella Gamaralalage Jagath Premakumara

ICLEI South Asia: Anuradha Adhikari, Rahul Singh, Sumskrutha Shroff, Ritu Thakur, Bedoshruti Sadhukhan and Soumya Chaturvedula

Design and layout by: ICLEI South Asia, New Delhi, India

Disclaimer

The 'Compendium of Technologies for Plastic Waste Recycling and Processing' publication is prepared under the Project 'Development of Holistic Strategy and Action Plan for Plastic Waste Management in Greater Hyderabad Municipal Corporation,' supported by the IGES Centre Collaborating with UNEP on Environmental Technologies (CCET) with ICLEI – Local Governments for Sustainability, South Asia as technical implementation partner. The Compendium is prepared based on primary and secondary research and presents a snapshot of available technologies for recycling and processing plastic waste. The views expressed in this document do not necessarily represent the official decision or stated policy of the United Nations Environment Programme. The citing of trade names in this document does not constitute endorsement.

Abbreviations

AFRs	Alternative Fuel and Raw Materials
BBMP	Bruhat Bengaluru Mahanagara Palike
BIS	Bureau of Indian Standards
BTU	British Thermal Unit
CAPEX	Capital Expenditure
CEMS	Central Emission Monitoring System
CMP	Central Mixing Plant
CPCB	Central Pollution Control Board
CRRI	Central Road Research Institute
DRD	Double Rotor Disk
EPR	Extended Producer Responsibility
ER	Equivalence Ratio
ESP	Electrostatic Precipitator
FICCI	Federation of Indian Chambers of Commerce & Industry
FMCG	Fast Moving Consumer Good
GAIA	Global Alliance for Incinerator Alternatives
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
INR	Indian Rupee
IS	Indian Standards
ISWM	Integrated Solid Waste Management
LDO	Low Diesel Oil
LDPE	Low Density Polyethylene
LEV	Local Exhaust Ventilator
MLP	Multi Layered Plastics
MOEFCC	Ministry of Environment, Forest and Climate Change
MOHUA	Ministry of Housing and Urban Affairs
MORTH	Ministry of Road Transport and Highway
MoU	Memorandum of Understandings
MRC	Material Recovery Centre
OPEX	Operating Expenses
PAH	Polycyclic Aromatic Hydrocarbons
PCA	Plastic Coated Aggregates
PET	Polyethylene terephthalate
PLA	Polylactic Acid
PM	Particulate Matter
PP	Polypropylene
PPP	Public Private Partnership
PS	Polystyrene
PVC	Poly Vinyl Chloride

PVDC	Polyvinylidene Chloride
PWM	Plastic Waste Management
RDF	Refuse Derived Fuel
REEL	Ramky Enviro Engineers Limited
RPF	Refuse Derived Paper and Plastic Densified Fuel
SCF	Segregated Combustible Fractions
SRF	Solid Recovered Fuel
SPCB	State Pollution Control Board
SUPs	Single Use Plastics
SWM	Solid Waste Management
TOC	Total Organic Carbon
TPA	Tonnes per Annum
TPD	Tonnes per Day
ULBs	Urban Local Body
USD	United States Dollar
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compounds

Table of Contents

List of Figures

List of Tables

1. Introduction

Plastic pollution is one of the fastest-growing threats in the world[1], and has even been defined as a pandemic[2]. It is estimated that of the 8.3 billion tonnes of plastic introduced in the market between 1950 and 2015, 5.8 billion tonnes has ended up as waste. Of that, 12% has been incinerated, 9% recycled, and around 60% discharged in landfills or the environment[3]. This ever-increasing burden of plastic waste has become a challenge for local authorities. Due to the absence of holistic plastic waste management systems most South Asian cities neither collect nor process plastic waste scientifically, which leads to much of it entering oceans, rivers, and fertile lands, which impacts on natural ecosystems. Plastic waste is known to have direct impacts on the environment and public health, including animals, by inducing physical and chemical toxicity through open dumping and open burning. Recent studies indicate that approximately 8.3 billion tonnes of plastic waste have accumulated since the early 1950s, 79% of which has ended up in either disposal sites or the natural environment, and almost 8 million tonnes in the ocean every year, adding to the estimated 150 million tonnes that currently circulate in marine environments[4]. Indiscriminate littering, unorganised management and non-biodegradability of plastic waste have led to several environmental concerns.

Addressing the growing menace of plastic waste requires adopting a holistic approach across the entire waste management hierarchy, which is a globally recognised concept embracing the use and progression of policies and strategies from most preferred to least preferred approaches to managing waste. This hierarchy focuses on precautionary and preventive principles and promotes minimization of waste generation at source. Once waste is produced, it encourages reuse, recycling, recovery, and lastly disposal. It also forms an integral part of the vision and mission of moving economies from the linear model of production, consumption and disposal towards the circular economy, thereby maximising the economic potential of materials by ensuring their continuous flow through the economy without relying on new raw materials that are increasingly becoming costly, both financially and environmentally. Some of the technical and technological approaches currently available to managing plastic waste that are in line with the waste management hierarchy are indicated in Table 1, below.

[1]Source: https://www.earth.com/news/plastic-pollution-health-threats/, Retrieved October 11, 2019

[2]Source: https://www.unenvironment.org/cep/news/blogpost/plastic-pollution-pandemic, Retrieved December 5, 2019

[3]Source:https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/554/original/UNEP-CHW-PWPWG.1-INF-4.English.pdf?1594295332, Retrieved December 12, 2019

[4]Source:https://wedocs.unep.org/bitstream/handle/20.500.11822/31555/Marine_Plastic_Pollution.pdf?sequence=1&isAllowed=y, Retrieved December 12, 2020

Table 1: Examples of technical and technological interventions for Plastic Waste Management across waste management hierarchy

Stage of Waste Management Hierarchy	Examples of Technical/Technological Interventions
Prevention: Waste minimisation by reducing what is not required, redesigning goods and business models to minimise plastic waste generation	- Use of Poly-Lactic Acid (PLA) extracted from vegetable starch to make biodegradable carry bags[5] - Use of water hyacinths or mushrooms to make lightweight, cushioned packaging cartons[6,7] - Ensure interventions through Extended Producer Responsibility (EPR) by dominant FMCG brands identified through brand audits
Reuse: Check, clean, repair products or components of products to reuse them without any pre-processing	- Up-cycling of plastic items to make wall art, decoration at religious/cultural ceremonies, etc.
Recycle: Processing of waste to recover commercially valuable material	- Mechanical recycling of PET bottles to manufacture fibre for textile industries[8] - Mechanical recycling of HDPE/PP products to make garbage bags, pesticide containers, twine, etc.
Recovery: Recovering energy before final disposal of waste	- Chemical recycling of plastic to liquid (pyrolysis) or gaseous (gasification) fuel production - Use of plastic waste as solid fuel, i.e. Refuse Derive Fuel (RDF) for co-processing in cement kilns
Disposal: Safe disposal of inert residual waste at sanitary landfill	

(Adapted from various sources)

Considering the information available, it is evident that the various technical and technological options for prevention of plastic waste in India are at a nascent stage. Also, accessibility and affordability play a major role in ensuring alternatives to SUPs are adapted at a larger scale. Therefore, at present, collecting plastic waste and channelizing it into efficient recycling and recovery routes is considered the pre-eminent strategy to reduce environmental, economic and social costs.

---

[5] Source: https://www.researchgate.net/publication/336936495_Polylactic_Acid_PLA_As_A_Bioplastic_And_Its_Possible_Applications_In_The_Food_Industry, Retrieved May 1, 2021

[6] Source:https://www.researchgate.net/publication/339998770_Tensile_Strength_of_Paper_Produced_from_Different_Body_Parts_of_Water_Hyacinth, Retrieved May 1, 2021

[7] Source: https://news.yahoo.com/ikea-commits-biodegradable-mushroom-packaging-220023480.html?guccounter=1, Retrieved December 20, 2020

[8] Source: https://www.thehindu.com/sci-tech/energy-and-environment/plastic-bottles-turn-mattresses-quilts-much-more/article18714374.ece, Retrieved November 10, 2019

Brand Auditing: Accounting the role of FMCG Sector in generating plastic waste

The Fast Moving Consumer Goods (FMCG) and processed food industries have been identified as the biggest consumers of low value plastics for their packaging and delivery systems. Brand auditing exercises help identify and monitor the types and volumes of plastic waste generated in a city and also help in linking the plastic and other packaging waste to particular brands. Such data can be utilized to identify major polluters and hold them accountable in line with the Extended Producer Responsibility (EPR). Brand auditing also enables use of instruments such as product take-back schemes, pay-as-you-throw and waste user fees, advance disposal fees and deposit refund schemes, which would result in enhanced recycling rates. Data therefrom can be assessed and used by municipal officials to design collection systems and schedules, develop policies, identify relevant technologies, and so on.

The methodology for conducting brand auditing is straightforward, involving taking samples of plastic waste at different points in a city (including transfer stations, dumpsites and landfills), and manually sorting it by:

- Types of plastic waste based on end use (Household Products, Food Packaging, Personal Care, Smoking Materials, Fishing Gear)
- Categories of plastic packaging (Single-layer, Multi-layer, etc.)
- Types of Plastic Resin Code

Identification of parent brands is conducted at a later stage by collating data from on-ground sorting during brand auditing. Details of the methodology used for conducting brand audits can be accessed at: https://www.breakfreefromplastic.org/brandaudittoolkit/.

Global Alliance for Incinerator Alternatives (GAIA) conducted a brand audit of 250 sites across 15 cities in 18 states in India (2018). The study identified 3,847 brands, one-third of which were international – PepsiCo: 27.70%, Perfetti van Malle: 14.45%, Unilever: 11.66% and CocaCola: 10.51% – with the leading local contributor being Parle Products: 10.34%. For more information, access: https://www.no-burn.org/wp-content/uploads/India-BrandAuditReport_Final.pdf

A study based on Trucost's natural capital valuation framework suggests that increasing post-consumer plastics recycling (to 55%) and minimising landfilling (to a maximum of 10%) across Europe and North America would reduce the environmental cost of plastics by over 7.9 billion USD, in net terms. This result also accounts for the increased environmental impacts associated with waste collection and management and the direct economic gains associated with the recovered value of recycled plastics and recovered energy[9]. As per a study conducted by FICCI and Accenture, one tonne of plastic recycling in India is expected to save about 1.7 km^2 of landfill area and also lead to 1.39 million incremental jobs created in the plastic recycling industry[10].

[9]Source: https://plastics.americanchemistry.com/Plastics-and-Sustainability.pdf, , Retrieved December 18, 2020

[10]Source: https://ficcices.in/pdf/FICCI-Accenture_Circular%20Economy%20Report_OptVer.pdf, Retrieved January 20, 2021

Though plastic recycling is mainly prominent across developed nations, there is a much wider scope of recycling in developing nations such as India, for several reasons[11]. These reasons include the prevalence of the informal sector, which proactively undertakes collection, sorting, cleaning, and reuse of waste or used materials and small-scale recycling activities at low labor cost, and the needs of manufacturers, which through low transport and raw materials costs gives them an edge in this competitive sphere. Further, innovative use of scrap machinery often leads to low entry costs for processing and manufacture.

However, the recycling landscape of India does not pose a promising picture as of now. Only 60% of plastic waste from the municipal solid waste stream is recycled while the rest is either dumped openly or disposed in sanitary landfills[12]. The fact that 94% of generated plastic waste is recyclable[13] sets forth the potential recycling trajectory for the country. However, the opportunities remain untapped due to the lack of technical, financial and infrastructural capacities within ULBs. Existing recycling facilities are financially stressed, unable to tap the market potential, and in most cases operate in an unorganised manner to evade costly environmental control mechanisms. As of 2018–19, 185 plastic recycling units were registered in 30 states of India whereas 1,080 unregistered units were operating in 12 states[14]. The magnitude of underreporting and non-updating of databases on recycling units is evident from the fact that Greater Hyderabad Municipal Corporation itself houses about 500 unregistered and 541 registered plastic recycling and manufacturing units[15]. The unregistered units not only pose an environmental threat by releasing uncontrolled gaseous emissions and liquid effluents but also cause potential health risks to workers. Additionally, the lack of adequate pre-processing and inefficient or non-use of appropriate equipment and technology results in production of substandard end products in the unregistered units.

The '**Compendium of Technologies for Plastic Waste Recycling and Processing**' was produced in the course of the project, 'Enhancing Circular Economy Perspectives - Plastic Waste Management Strategy and Action Plan for Greater Hyderabad Municipal Corporation', funded by the Institute for Global Environment Strategies (IGES) Centre Collaborating with UNEP on Environmental Technologies (CCET), the United Nations Environment Programme-International Environmental Technology Centre (UNEP-IETC) Japan, and ICLEI South Asia. It covers the various plastic waste recycling and processing technologies available and associated environmental control measures and is aimed at raising awareness amongst urban planners, decision-makers, private sectors and plastic waste recycling units, thereby supporting better decision making.

[11]Source: https://www.mdpi.com/2313-4321/2/4/24, Retrieved December 13, 2020
[12] Source: http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf, Retrieved September 15, 2019
[13] Source: https://optoce.no/wp-content/uploads/2019/03/CPCBCIPET-Assessment-and-Quantification-of-Plastics-Waste_2015.pdf, Retrieved June 10, 2019
[14] Source: https://cpcb.nic.in/uploads/plasticwaste/Annual_Report_2018-19_PWM.pdf, Retrieved April 5, 2019
[15] Discussion with TSPCB and TAAPMA, November, 2019

2. Key Factors for Selection of Appropriate Technology

While exploring and selecting plastic waste recycling and processing technologies, ULBs should assess the following aspects while also addressing local needs and conditions adequately and appropriately:

- Quantum and characterisation of plastic waste
- Level of pre-processing
- Environmental control
- Financial sustainability
- Institutional capabilities
- Technical and technological appropriateness of systems for waste handling and disposal

These are explained below.

Quantification and characterisation of plastic waste sets the premise for selection of recycling and processing technologies. The quantum of waste available is of primary importance to ensure continuous supply of minimum feedstock for sustained operations of recycling and processing facilities.

Pre-processing of plastic waste not only reduces operational costs but also enhances recycling efficiency. Different plastic types are not compatible for co-processing with each other due to their inherent properties, and require different processing methods. For example, a small amount of PVC present in a PET recycling stream tends to degrade the quality of recycled PET resin due to hydrochloric acid gas produced from PVC at a higher temperature required to melt and reprocess PET. Conversely, PET in a PVC recycle stream will also form solid lumps of undispersed crystalline PET, which significantly reduces the value of the recycled material. In other words, the chemical constituents of plastics have a direct bearing on the type of recycling and processing technology needed. Higher calorific values indicate the suitability of plastic waste as feedstock in waste to energy plants or RDF, and higher volumes of volatile matter can favour liquid oil production. Plastics with high ash content lowers the production of liquid oil and increases the gaseous yield and char formation.

Environmental controls ensure measures are in place to capture toxic emissions like dioxins, NOx, SOx, chloride or Volatile Organic Carbons (VOCs)

Financial sustainability of the processing system over the long term needs to be ensured, through considering several cost recovery mechanisms including user fees, sale of end products, market demand, municipal funds and grants from State and Central Governments, loans and funding from the private sector through Public Private Partnerships (PPP).

Institutional capabilities of ULBs to be strengthened to ensure appropriate monitoring and supervision of the processing units. A management information system should be set up to record and monitor all data on PWM and the growth of unregistered informal processing units.

Table 2: Appropriate Recycling Technologies for Different Plastic Resins and their Recycled Products[16]

Plastic Resin	Recycling Technology	Recycled Products
Polyethylene Terephthalate (PET): typically used for many bottle applications owing to factors of low cost, light weight, and shatter resistance	Mechanical Recycling	Fibres for textile industry, mineral/drinking water bottles, cosmetics bottles
High Density Polyethylene (HDPE): typically used in bottles, carry bags, milk pouches, recycle bins	Mechanical Recycling	Black HDPE pipes, household plastic items (boxes, buckets, toys, bottles for detergents), chairs, construction materials
Low Density Polyethylene (LDPE): used in plastic bags, various containers, dispensing bottles, wash bottles, tubing	Mechanical Recycling	Black dustbin bags, bin liners, flexible packaging, carrier bags, tubes, agricultural mulch film, agricultural sheets, construction film, cling-film, heavy duty sacks
Polypropylene (PP): used for auto parts, industrial fibers, food containers	Mechanical Recycling	Twine, cement bags, black dustbin bags, kitchen container lids, pipes, pallets, boxes, furniture, car parts, buckets, fibers, milk crates
Polystyrene (PS): used for food service packaging, disposable cups, tray pitchers, refrigerators, liners, etc.	Chemical recycling or co-processing	Clothes hangers, park benches, flower pots, toys, spoons, cutlery, picture frames, seeding containers
Others (Mixed Plastic Waste): used in thermoset plastics, multilayer and laminates, Bakelite, polycarbonates, etc.	Chemical recycling or co-processing Special extrusion process by UFlex Extruder	CDs, pallets, floors, roofs, furniture, sheeting, benches, shoe soles

Recycling of Black Coloured Plastic[17]

Black coloured plastic is of two types, carbon black and master batch. While master batch is preferred for recycling, carbon black is left unused. Carbon black plastic is manufactured from hydrocarbons that are charred in the absence of oxygen and then activated. This leads to harmful emissions during recycling when using extrusion technology. On the other hand, master batch is made using regular pigments imparted from hydrocarbons which can be recycled without releasing any harmful emissions.

[16] Collated from different sources

[17] As per discussion with Manager, Godrej Consumer Products Limited, Hyderabad, 2019

The selection and adoption of PWM processing technologies should be based on a set of defined criteria and subjected to a detailed due diligence study, which could ascertain the appropriacy of the technology for the local conditions in respective cities. Additionally, in cases where local authorities feel challenged to ensure appropriate selection processes, they may seek external expertise to ascertain the most viable solutions.

Table 3 below presents key factors to be considered when selecting processing technologies for plastic waste:

Table 3: Key factors for selection of plastic waste management technologies[18]

Key Factors	Criteria/Local Conditions	Mechanical Recycling	Plastic to Road	Plastic to Fuel	Gasification	Co-processing in Cement Kiln
Quantum and characterisation of plastic waste	Quantity of plastic waste	Minimum of 1 TPD	Plastic waste amounting to 8–10% of bituminous mix	Minimum 5 TPD	Still at pilot scale	100 TPD of segregated waste and above
	Types of plastic waste	PET, HDPE, PP, LDPE	Non-recyclables (except PVC)	Non-recyclables (except PVC)	Non-recyclables	Non-recyclables
	Parameters under consideration	- All thermoplastics except PVC and PS due to presence of additives and potential emission of dioxin and furans. - To ensure the waste fraction is free from contaminants (dust, oil etc). - 20–30% of virgin plastic along with 70% sorted plastic of specific types and colours, to ensure high quality output	- PVC should not be used as thermal degradation of PVC results in emissions of harmful gases like hydrochloric acid. - Black coloured plastic waste is a result of repeated recycling and should not be used. - Dust and other impurities not to exceed 1%.	- Calorific value - Ash content - Volatile content - Moisture content	- Calorific value - Ash content - Volatile content - Moisture content	- Non-recyclable waste having minimum calorific value of 1,500 kcal/kg - Moisture, preferably <20% - Size, 2D <120 mm, 3D <70 mm subject to process limitations of specific cement plant - Chlorine, preferably <0.7% depending on particular raw mix and fuel mix - Sulphur, <2% depending on particular raw mix and fuel mix - Free of restricted items (polyvinyl chloride, explosives, batteries, aerosol containers, biomedical waste)

[18] Adopted from various sources including CPHEEO Manual on Municipal Solid Waste Management; Recommended guidelines for plastic recycling unit by Institute for Industrial Development (IID) https://www.youtube.com/watch?v=37W6FZKJmm8; Retrieved December, 2019, Discussion with Pyrogreen Energy Pvt. Ltd., Hyderabad, 2019

Key Factors	Criteria/Local Conditions	Mechanical Recycling	Plastic to Road	Plastic to Fuel	Gasification	Co-processing in Cement Kiln
Level of pre-processing	Requirement for segregation	Yes; intensive segregation	Yes; medium intensive segregation	Yes; medium intensive segregation	Yes; medium intensive segregation	Yes; intensive segregation
Environmental soundness	Facility location	Orange category industry, to be established in demarcated industrial zone, away from residential area		Orange category industry, to be established in demarcated industrial zone, away from residential area	Plant should be equipped with environmental control measures to restrict release of particulate matter, tars, nitrogen and sulphur oxides, dioxins and furans, hydrocarbons, and carbon monoxide into ambient atmosphere	Plant should be equipped with environmental control measures to restrict toxic gaseous emission and treat liquid effluent
	Land requirement	1 acre for 1 TPD of plant	NA	0.14 acre for 5 TPD	10 acres/MW[19]	For 300 TPD of segregated/pre-sorted MSW: approx. 5 acres of land
	Toxic emissions	- Gases, vapours or fumes are released during melting process of plastics in extrusion, the control of which requires extruders equipped with appropriate LEV system.	- Gaseous emission can result if temperature for melting plastic not maintained. - Plastic waste should be tested for impurities and melt flow to avoid emissions.	- Dioxin and furan can be generated if temperature range not maintained.	- Highly reduced scope of emissions of dioxin and furans. - Hydrogen Chloride in syngas needs to be managed.	- Low to moderate (dust, aerosols). Can be very high if RDF is not burnt at required temperature. - Odour issues - Burning of RDF below 850°C for less than 2 seconds residence time can pose serious problems for health and environment.

[19] Source: http://hh.diva-portal.org/smash/get/diva2:935652/FULLTEXT02.pdf; Retrieved May 3, 2021

Key Factors	Criteria/Local Conditions	Mechanical Recycling	Plastic to Road	Plastic to Fuel	Gasification	Co-processing in Cement Kiln
Technical and technological appropriateness	Technology is at mature stage	Technology available and practiced widely	Well established technology in India	Emerging technology in India	Emerging technology in India	Well developed; quality of RDF is based on end use.
Financial Cost	Indicative Capital Investment	Capex: 10–20 million INR (0.13–0.27 million USD) for 1 TPD of plant	--	Capex: 25 million INR (0.33 million USD) for 5 TPD of plant	Capex: 150–180 million INR/MW[20] (2–2.4 million USD/MW). Capital investment and operating and maintenance costs are significant; economics is the primary reason for the limited number of commercial-scale facilities.	Typically 170–200 million INR (2.30–2.71 million USD) for 500 TPD plant
	Market for products/by-products	Market for recycled plastic is established in India; products such as garbage bags, pesticide containers, lids for kitchen containers, twine, etc. are made extensively, and rPET is used in textile industry.	Established practice in India—adopted in 15 states	Furnace oil is produced directly from the system; distiller can be used to produce oil for use in generators; oil is sold at 36 INR/litre (0.49 USD/litre), and usable by any industry requiring steam with boiler facilities.	Syngas, which can be further processed to make fuel/diesel.	Good market potential for RDF.

[20] Source: https://ankurscientific.com/blog/2018/11/25/what-is-the-cost-of-waste-to-energy-projects-in-india/#:~:text=The%20cost%20of%20installing%20a,kWh%20(coal%20to%20solar; Retrieved May 3, 2021

Key Factors	Criteria/Local Conditions	Mechanical Recycling	Plastic to Road	Plastic to Fuel	Gasification	Co-processing in Cement Kiln
Institutional Requirements	Technical and operational Skills	Technically qualified, experienced and semi-skilled staff	Technically qualified and semi-skilled staff	Technically qualified, experienced and highly skilled staff	Technically qualified, experienced and highly skilled staff	Technically qualified, experienced and semi-skilled staff

3. Plastic Waste Recycling and Processing Technologies

The Guidelines for Recycling of Plastic (IS 14534:1998) classifies various plastic recycling processes, as follows:

- **Primary Recycling**: Also known as 'closed loop recycling', this refers to the reuse of products in their original structure. However, the process is limited by the number of cycles for each material.
- **Secondary or Mechanical Recycling**: This implies application of the material used, without changing the chemical structure, for a new application. Only thermoplastic can be used for mechanical recycling as it can be re-melted and re-processed into end products. Mechanical recycling involves no polymer alternation during the process and typically involves physical methods like sorting, segregating, washing, shredding and pelletisation based on the requirements of subsequent stages. However, the process downgrades the quality of the material in each cycle due to the low molecular weight of the recycled resin. Mechanically recycled plastics may contain both recycled and virgin plastics depending on the level of quality desired for the product.
- **Feedstock or Chemical Recycling**: This process involves a change in the chemical structure of the material to enable the resulting chemicals to be used to produce the original material again. This is essentially a depolymerisation process where plastic polymers are broken into monomers and oligomers, which can be used again to manufacture alternative virgin materials. Depolymerisation has successfully been employed to recover monomers from PET, polyamides such as nylons and polyurethanes. Since recovered resins can be returned to their virgin resin-like state, this offers the potential to recover valuable feedstock from products that are economically challenging to recycle. Chemical or feedstock recycling includes conversion processes such as pyrolysis, gasification, hydrogenation, dehalogenation, thermal cracking, chemical depolymerization and hydrolysis.
- **Energy Recovery or Quaternary Recycling**: This process refers to the recovery of the energy content of plastic through incineration.

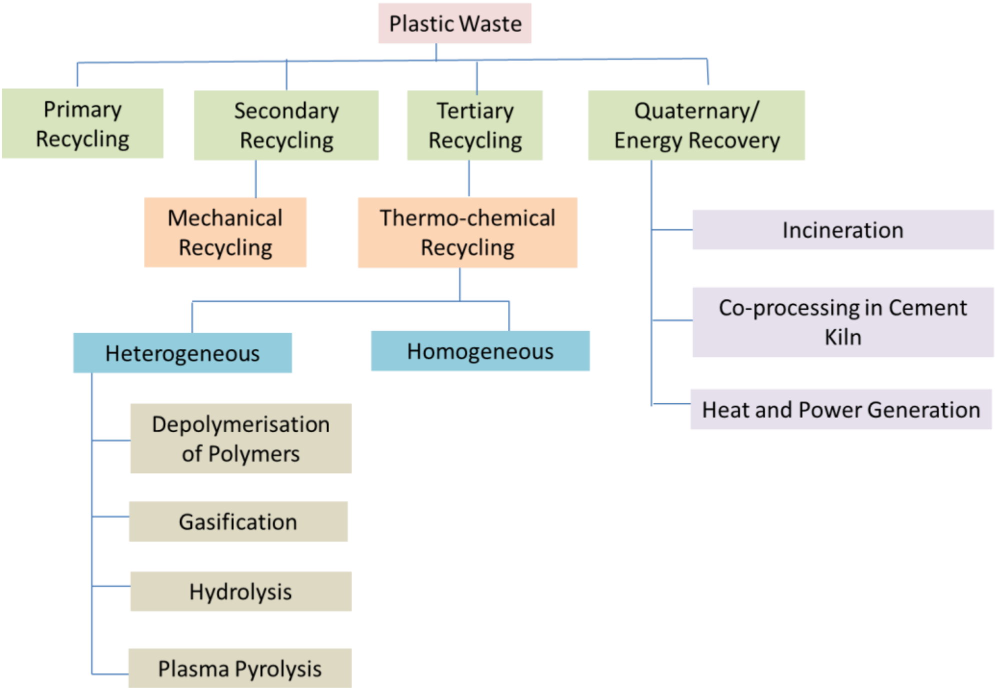

Figure 1: Types of plastic waste recycling and processing technologies

Table 4 below illustrates the key merits and demerits of the processing technologies indicated above.

Table 4: Advantages and limitations of plastic recycling and processing technologies[21]

Recycling Process	Advantages	Limitations
Primary Recycling	Simple and low cost	Limit on the number of cycles for each material
Mechanical Recycling	Cost-effective; efficient; well-known; 27% relative emission reduction while replacing virgin PET with 100% recycled PET[22]	Deterioration of product's properties; pre-treatment; very little high-end equipment is found in developing countries and requires importing, manufacturing locally or use of improvised equipment
Chemical Recycling	Simple technology; most sustainable option considering monomer is obtained from this process	Mainly limited to condensation polymers; expensive process and requires significant subsidies due to low price of petrochemicals in contrast to high process and plant costs for chemically recycled polymers
Quaternary Recycling	Generates considerable energy from polymers; most suitable measure for mixed plastic	Not environmentally acceptable owing to health risks from airborne toxic substances

[21]Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2873020/, Retrieved December 13, 2020 & https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/554/original/UNEP-CHW-PWPWG.1-INF-4.English.pdf?1594295332 , Retrieved December 12, 2020
[22] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2873020/, Retrieved December 13, 2020

Depending on the physical and chemical characteristics, collected plastic waste can be either sent to mechanical reprocessing, feedstock/chemical recycling processes or energy recovery and landfill. However, one process cannot be chosen for all commercial plastics currently introduced in the market. The main factors affecting decisions on technology selection, along with financial implications, are the composition of plastics in terms of polymer type (HDPE, LDPE, PP, PS, EPS, PET, PVC) and the fraction of non-polymeric materials (including multi-layered plastics and composites). These characteristics affect the overall design of the system starting with the sorting facility, where the mixed plastic waste is received, up to the recycling or recovery processes.

Table 5: Categories of polymers and products under each polymer type

PET	Polyethylene Terephthalate	
HDPE	High Density Polyethylene	
PVC	Polyvinyl Chloride	
LDPE	Low Density Polyethylene	
PP	Polypropylene	
PS	Polystyrene	
OTHER	Others – CDs, multi layer plastics	

3.1. Extrusion

Plastics extrusion is a high-volume manufacturing process in which homogenised waste plastic is melted and turned into pellets. Plastic material in the form of pellets or granules is gravity fed through a hopper into an extruder, essentially a rotating screw surrounded by a heated barrel, where it is mixed, melted and pumped through a die which gives it a shape. However, such extruders cannot be used for recycling multi-layered plastics (MLP).

3.1.1. Feedstock for Extrusion

All types of thermoplastic can be recycled through extrusion technology except polyvinyl chloride (PVC) products, since they contain different additives, determined by their application. The efficiency of the technology depends on the homogeneity of the plastic waste. Feedstock should be segregated meticulously and be free of contaminants such as dust, oil and chemicals to ensure high quality end products. A minimum of 20–30% virgin plastic along with 70% sorted plastic of specific types and colours is required to maintain the quality of recycled products.

3.1.2. Process of Extrusion

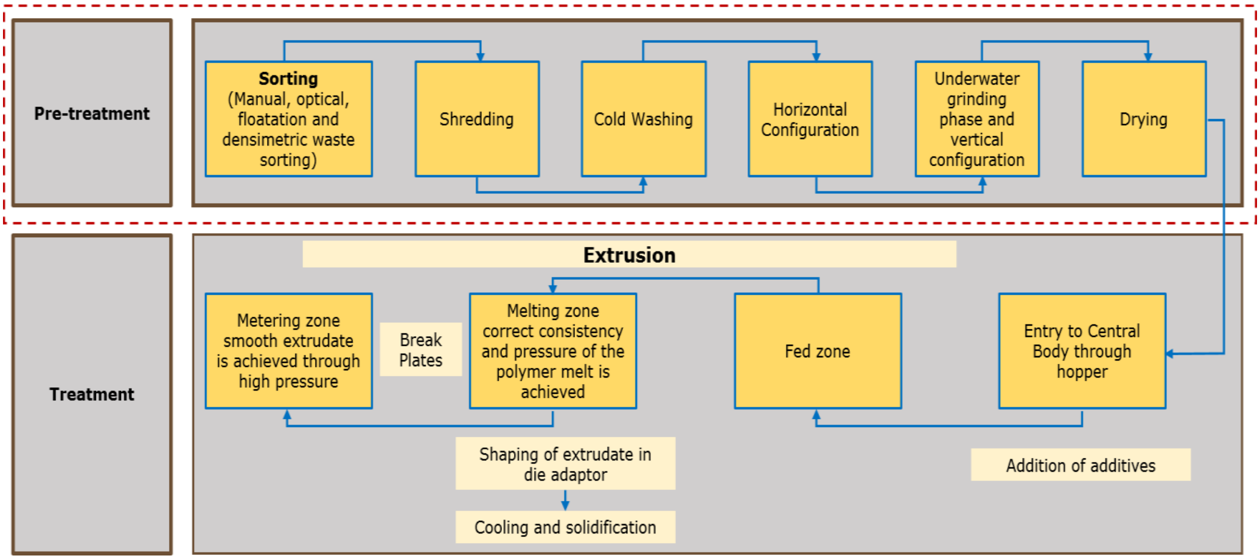

Figure 2: Process flow of extrusion[23]

Pre-treatment[24]: The plastic waste must be sorted according to its resin/SPI code (from 1 to 7) as the efficiency of the technology depends on the homogeneity of the waste. **Manual sorting, optical waste sorting, floatation waste sorting and densimetric waste sorting** can be employed for this process. After sorting, different types of plastics are shredded and washed in cold water to remove contaminants such as paper labels, glue, dust, adhesive tape and other residues. The waste is then moved to horizontal then vertical centrifuges to remove leftover impurities and residues. The cleaned material is then either sun-dried or air-dried depending on the available technology. Alternatively, agglomeration can be used during the pre-treatment stage, which consists of heating the plastic waste to just below its melting point to reduce its size, then cutting it into small pieces. This produces an irregular grain, often called crumbs or granules.

[23] Adapted from various sources
[24] Source: https://www.paprec.com/en/understanding-recycling/recycling-plastic/sorting-plastic-waste, Retrieved November, 2019

Figure 3: Shredder and washing and dryer machine[25]

Treatment: The shredded plastic material/granules are fed into the extruder (or 'central body') through a hopper. The plastic material enters a rotating screw which pushes the material forward into the barrel. Additives such as colourants and UV inhibitors can be mixed with the granules in the hopper. The rotating screw forces the plastic material forward into the barrel, which is heated to the desired melt temperature depending upon the resin. A heating profile is set for the barrel to provide controlled heat zones that gradually increase the temperature of the barrel from the rear. This helps the plastic resins/granules to melt gradually while being pushed through the barrel and lowers the risk of overheating which may cause degradation of the polymer.

[25]Source: https://www.indiamart.com/proddetail/plastic-waste-grinder-15025996091.html, Retrieved May 5, 2021 and https://www.indiamart.com/proddetail/waste-plastic-washing-plant-6394538797.html, Retrieved May 5, 2021

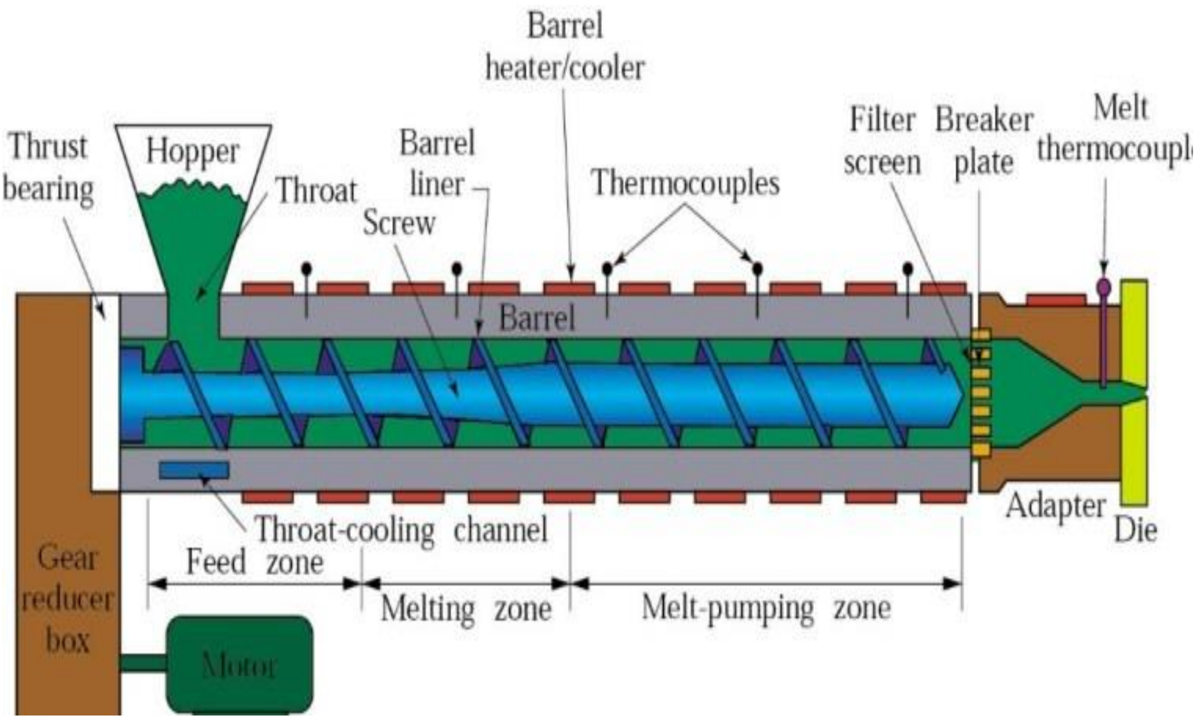

Figure 4: Plastic extruder machine[26]

As well as in heating, the screw barrel helps in pumping, mixing and pressurising. The screw is divided into three zones in the following order**: Feed zone** (for conveying material to the next zone), **Melt zone** (granules are completely melted and correct consistency and pressure of the polymer are achieved) and **Metering zone (**a smooth extrudate is achieved through high pressure). As each zone has a dedicated role it is important to determine the ratio of lengths between the feeding, transition and metering zones of the screw.

After the polymer is melted and mixed it is delivered to a die which forms the extrudate into a prescribed shape[27]. As soon as the extrudate exits the die it needs to be cooled and solidified, which is usually achieved by pulling it through a water bath. The extruded plastic is pulled using a puller and subsequently cut into pellets using a wind-up or cut-off machine.

Other techniques for decontamination of plastic waste

The most common method for removing labels, glue and other contaminants from PET bottles is through caustic soda (NaOH) at 70°C and 75°C, which is an aggressive treatment measure. However, this requires safety measures for workers and protection of equipment from corrosion.

PAV GmbH & Co. Vertriebs KG, Berlin[28] have developed a new process in which a biodegradable mixture containing citric acid, vegetable oils and yeast bacteria is used for cleaning PET bottles,

[26] Source: https://www.researchgate.net/figure/Typical-plastic-extruder-diagram_fig1_329789991, Retrieved May 5, 2021
[27] Source: http://www.industrialextrusionmachinery.com/types_of_plastic_extruders.html, Retrieved January 24, 2020
[28] Source: https://www.kunststoffe.de/en/specialized-information/technology-report/artikel/enzymes-in-the-plastics-industry-7662047.html?search.highlight=plastic%20recycling, Retrieved November 20, 2019

which helps in removing glue and other contaminants at room temperature. Nearly 85% of biodegradation takes place in 48 hours. This makes it the preferred option when compared to use of caustic soda. In this process, PET bottles are initially regranulated while in a dry state, which helps to remove over 90% of the label material to be separated using gravity. After the entire process, optical scanning of PET flakes takes place from both sides to sort by colour, and the reclaimed PET flakes can be processed as fibres or films.

Another technology, under development by Aimplas, Valencia, is the use of enzymes in the recycling process that can remove odours in the washing stage.

MAS Maschinen-und Anglagenbau Schulz GmbH[29] has developed a new process by which plastic waste can be cleaned and dried simultaneously. Generally, plastic waste with contaminants that can be rubbed off can be used for processing.

Factors impacting Extrusion: The success of the extrusion process depends on the identification, controlling and monitoring of several parameters. Five key parameters defining the stability of the extrusion process are:

1. **Melting temperature of the plastic**
   - Optimal temperature maximises uniform fluidity of the plastic and minimises the possibility for stress and warping of the final product.
   - Variables such as pressure and friction that build up in the barrel of the extruder mean that temperatures do not remain constant.
   - Heaters must be monitored, lowered, raised, or shut off as necessary to maintain constant temperatures within the extruder. Cooling fans and cast-in heater jackets can also help maintain proper extrusion temperatures.
2. **Speed of the screw**
   - The amount of extrusion increases with increasing screw speed, but the relationship is not linear. The extrusion amount of low-viscosity molten material is affected more by the screw rotation speed.
   - At high melting temperatures the amount of extrusion increases with increasing screw speed. However, at low melting temperatures the increase is minimal.
   - When the die resistance is low, the extrusion amount increases with the increase in screw rotation speed; the increase ratio is small at a higher die resistance.
3. **Extrusion pressure**
   - The amount of extrusion increases linearly as the head pressure increases.
   - Increasing the temperature of the die slows down the extrusion volume due to the influence of the head pressure. When the die resistance is high (the effective load area is small), the extrusion amount is more affected by the pressure at the head.
4. **Types of die**
   - Dies should be designed such that the residence time of the molten plastic does not reach the point beyond which degradation commences.
   - Extremely narrow channels can result in formation of die lines. For this reason the minimum dimension of a channel should not be less than 0.03 inches.

[29] Source: https://www.mas-austria.com/en/your-benefit-with-mas/a-dry-cleaning-system-drd, Retrieved May 3, 2021

5. **Cooling process**
   - Extruded parts can be cooled down by gases, liquids, or contact with heat-absorbing surfaces such as chill rolls or calibrators. The velocity of the cooling medium affects the product quality.

Advanced extruder technology for MLP waste

An advanced extruder from UFLEX Ltd. has recently been developed to recycle MLP. The UFLEX RE Lam-250 converts industrial waste into pellets and can be used to recycle both single layered and multi-layered plastic waste. Its double extruder technology can operate over a temperature range of 150°C to 225°C. The machine is also equipped with an air suction pump which captures the fumes generated during the melting of inks and adhesives, which prevents the release of harmful gases into the environment.[30]

One double-screw extruder system has a production capacity of 250 kg/hour, and costs 22.5 million INR (approx. 310,000 USD). The system comprises the following units:

- Belt conveyor
- Metal detector
- Compactor with water spray
- Vacuum loader
- Feeder for additive (specially designed)
- Double screw extruder design (100/33 & 120/10)
- Hydraulic screen changer system
- Water cooled Die Face Cutting (specially designed)
- Chute
- Centrifugal dewatering
- Air feeding system and silo
- Electric control cabinet
- Degassing system
- Tools and consumables

Optional extras: Dust collector; digital meter for displaying kWh, Amps, Volts at each phase; chiller.

3.1.3. Environmental Control

Gases, vapours and fumes are released during the process of melting of plastics in extrusion, which may have unpleasant odours and even be harmful to the health of workers. To control the gas

[30] Discussion with M/s Uflex Limited in July, 2019

emissions or fumes, extruders should be equipped with scrubbers. However, in practice, small-scale recycling units do not install scrubbers to capture the emissions generated. In the absence of any standards particularly for extrusion**, the emission standard for flue gas emissions from incinerators as directed by the Solid Waste Management (SWM) Rules, 2016 should be used for monitoring emissions from extruders**. The emission standards are provided in Table 6 below.

Table 6: Flue gas emission standards[31]

Parameters	Emission standard
Particulates	50 mg/Nm^3
HCl	50 mg/Nm^3
SO_2	200 mg/Nm^3
CO	100 mg/Nm^3
Total Organic Carbon (TOC)	20 mg/Nm^3
HF	4 mg/Nm^3
NOx (NO and NO_2 expressed as NO_2)	400 mg/Nm^3
Total dioxins and furans	0.1 mg TEQ/Nm^3
Cd + Th + their compounds	0.05 mg/Nm^3
Hg and its compounds	0.05 mg/Nm^3
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V + their compounds	0.5 mg/Nm^3

[31] Source: Solid Waste Management Rules, 2016.

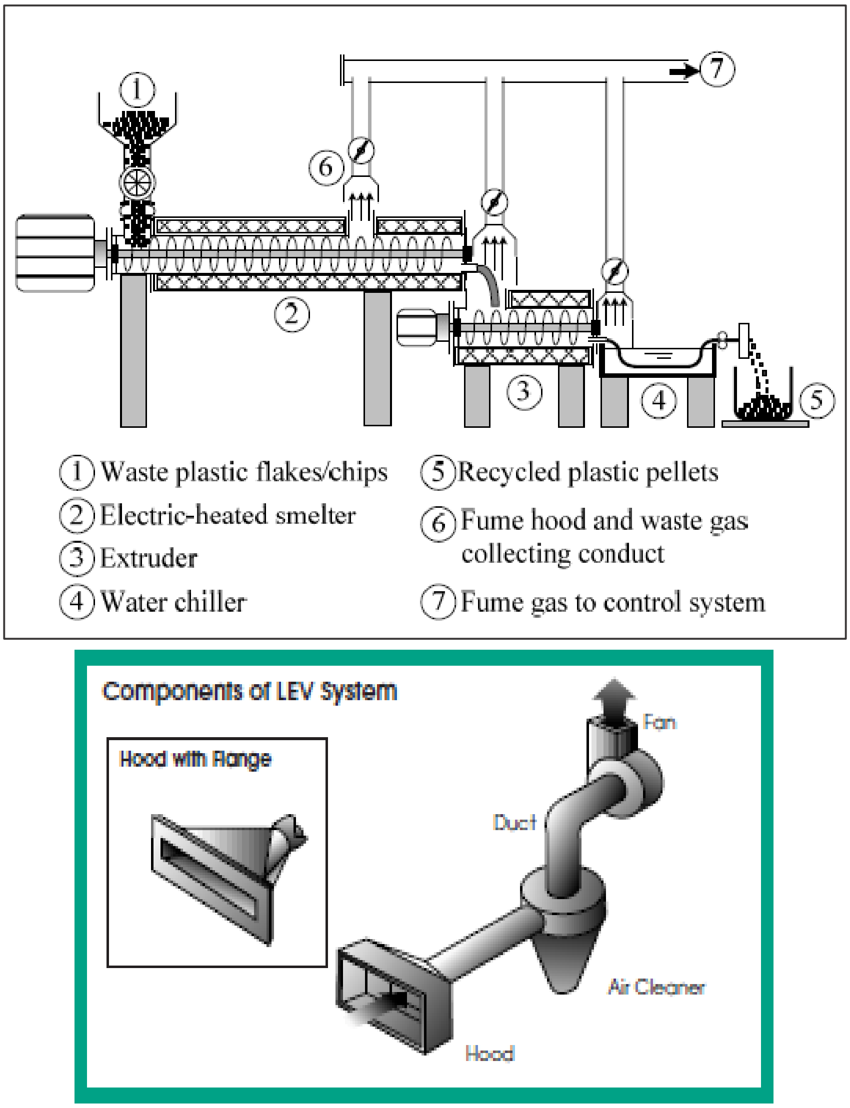

Figure 6: Schematic of emission control in extrusion (above), Components of a Local Exhaust Ventilator (LEV) (below)[32,33]

- **Emission Control Mechanisms:** Emitted fumes should be collected by two hoods, one set above the gas vent hole located at approximately the midpoint of the heated screw smelter and the other at the exit end of the smelter, also called a Local Exhaust Ventilation (LEV) system. The collected gas streams are then combined and conveyed to a control system. In general, an electrostatic precipitator (ESP) is used to remove the mists in the collected gas, the removal efficiency of which chiefly depends on the volume and electrostatic conductivity of the mists. Odorous Volatile Organic Compounds (VOCs) should be controlled to avoid complaints from neighbouring habitants resulting from odorous vent gases. Chemical scrubbing can be used to control waste gases with VOCs, and one of the most effective oxidants therefore is aqueous sodium hypochlorite. Some studies have also focused on the

[32] Source: https://aaqr.org/articles/aaqr-13-01-tn-0014.pdf , Retrieved December 13, 2020
[33] Source: https://www.dupont.com/content/dam/dupont/amer/us/en/transportation-industrial/public/documents/en/Ventilation_brochure_en_200108.pdf, Retrieved December 13, 2020

hypochlorite oxidation of aqueous organics such as benzene, toluene, xylenes, phenolates, aldehydes, and ketones.

- **An air cleaning device** is recommended as a responsible practice to remove airborne contaminants before discharging outside the workspace. Discharged air must comply with the permitted acceptable concentrations of contaminants according to the norms. Details of air cleaning devices are tabulated in Annexure 1. The exhaust stacks must be placed at a minimum distance of 15 m from air intake sources to prevent the discharge being fed back into the workspace. There must also be a sufficient supply of air brought into the building for effective operation of an LEV system. A portable LEV unit can be used for small-scale applications such as grinding or trim removal from plastics to capture and remove the low-toxicity dust from plastic parts.
- **Odour Control:** Sources of odour generated during plastic waste recycling processes are fumes produced by the hot (150 to 250°C) extrusion granulation process. Studies indicate that nylon recycling produces the smells of ammonia and burnt plastics and polypropylene (PP) plastic recycling produces mainly the smell of acrolein[34]. All the emitted VOCs are harmful to public health and the environment. Other studies have also reported various VOC emission factors or compounds.

3.1.4. Advantages and Limitations of the Extrusion Process

Advantages	Limitations
• High production volumes with very low cost per unit • Provides low-cost material to the moulding industry • Provides design flexibility • Advanced extruder machines can recycle multi-layered plastic	• Technology still needs certain amounts of virgin plastic to provide strength to pellets • PVC cannot be recycled due to the emission of HCl which can cause rusting in the extruder • Process requires good segregation to ensure uniform quality of end products • Small scale recycling industries do not install air pollution control measures

Plastic Waste Recycling Unit in Hyderabad-A Case Example from India

The plastic recycling unit within the ISWM (Ramky Enviro Engineers Ltd., or 'REEL') facility in Jawahar Nagar is an example of a well-organised facility under the Greater Hyderabad Municipal Corporation. The unit is an integrated facility with 250 kg/hour[35] processing capacity and includes washing, drying, pelletising and product manufacturing units. The facility processes almost 3 TPD of plastic on average. Extruded PE pellets are used for manufacturing HDPE bags of R9[36] quality. PET, PP pellets and additional PE pellets are sold to external recyclers. This unit is equipped with Local Exhaust Ventilation (LEV) to extract all gases as well as Volatile Organic Compounds (VOCs) formed inside the device. The facility also has a wastewater treatment facility where wastewater

---

[34] Source: https://aaqr.org/articles/aaqr-13-01-tn-0014.pdf, Retrieved December 13, 2020

[35] 250 Kg/hour for hard plastic and 80 Kg/hour for soft plastic

[36] More than 90% recycled plastic

from the washing of the plastic and the fumes extracted by the LEV system is filtered to remove all impurities from the washing process. The treated water is recirculated in the process for a period of two weeks to one month. Later, water in the system is replaced and the wastewater is collected in a tanker and delivered to the wastewater treatment system within the ISWM facility.

Figure 7: Washing plant (left), extrusion plant (center) and recycled plastic product manufacturing (right)

Recycling of PET Bottles in Japan

In Japan, PET bottles are sorted, collected, compressed, packaged and transported by municipalities to recycling units. At the recycling plant the waste is sorted to remove impurities, and the PET bottles are shredded and cleaned. Impurities and non-resins are removed and the remainder is turned into flakes and pellets for recycling. The recycled materials are then sent to textile and sheet-making plants, where they are melted down for fabricating textile and sheet products.

Originally, recycled PET was not used for beverage use due to hygiene concerns, odour-related problems, etc., therefore a combination of mechanical and chemical recycling methods was used for ‘Bottle to Bottle’ recycling based on the principles of monomerisation. The process helps remove impurities from flakes and performs polymerization under vacuum and high temperature, and the output is used as raw material for beverage-specific PET bottles[37]. Bottle to Bottle recycling is considered a model case study involving maximized product usage with minimal health and environment concerns.

According to the Japan Containers and Packaging Recycling Association, almost 1,227 business entities recycled 265,287 tonnes of PET bottles in 2019. Of the recycled bottles, 32.3% were recycled into textiles, 42.6% into plastic sheet, 22.3% into bottles and 2.8% into molded products. The recycling of PET bottles costs approximately 4.5 Yen/kg (0.041 USD/kg)[38].

[37] Source: https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf, Retrieved April 2, 2021
[38] Source: https://www.jcpra.or.jp/english/tabid/612/index.php, Retrieved April 5, 2021

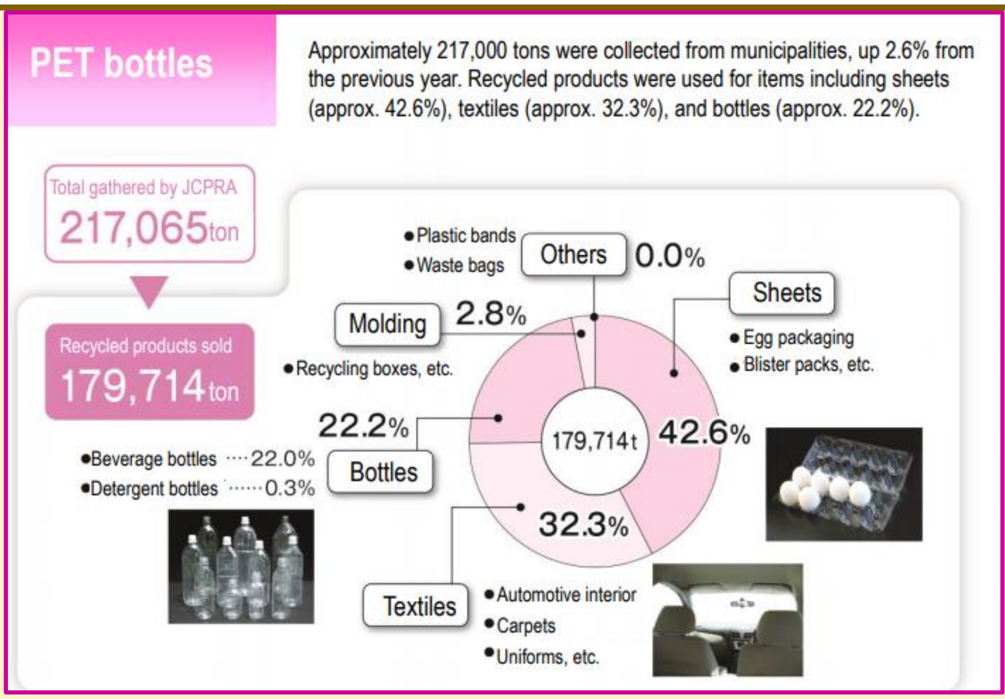

Figure 8: Utilization of recycled PET Bottles in Japan (2019)[39]

Teijin Limited became the world's first company to use chemical recycling technology to reclaim used PET bottles as PET resins. The company used its own proprietary decomposition method, which combines ethylene glycol and methanol to break down PET resin into dimethyl terephthalate for use as raw material for textiles and films. This technique was further modified to produce PET resin. In 2003 Teijin launched a facility with capacity to process around 62,000 tonnes/year of used PET bottles into 50,000 tonnes of PET resin for bottles. The recovered resin was approved by the Food Safety Commission of Japan's Cabinet Office for use as virgin material for PET bottles. However, due to the shortage of raw materials resulting from increased exports of waste PET bottles, Teijin Limited suspended its Bottle to Bottle PET bottle recycling programme in 2009 and continued with its Bottle to Fiber operations.

Similarly, Aies Co. Ltd. also developed a technique for manufacturing resin, involving breaking down PET bottles into high-purity monomer through de-polymerization. It established a new company, PET Reveres Co., Ltd. in 2004 which processes around 27,500 tonnes of PET bottles per year.

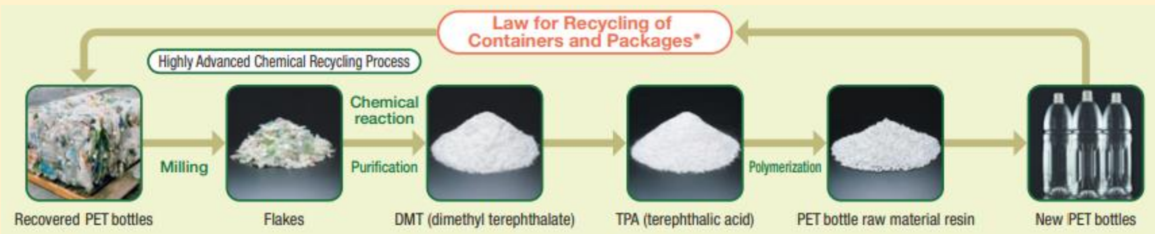

Figure 9: Recycling Technology for Production of New PET Bottles from used PET Bottles[40]

[39] Source: https://www.jcpra.or.jp/Portals/0/resource/eng/JCPRAdocuments202012.pdf, Retrieved May 3, 2021
[40] Source: https://www.teijin.com/csr/report/pdf/csr_05_en_all.pdf, Retrieved April 5, 2021

3.2. Plastic to Road

Use of plastic waste in road constriction is the viable alternative when mechanical recycling, chemical recycling or energy recovery from plastic waste are not available. This is a process of material recovery that does not require high-end segregation, while polystyrene (PS) and multi-layered plastics (MLP), which are usually difficult to recycle, are also used in the processes. According to Indian Road Congress (IRC), utilisation of waste plastics in bituminous construction in regulated amounts (about 5–10%) substantially improves the Marshall Stability, strength, fatigue life, and other desirable properties of bituminous mix, leading to improved longevity and pavement performance.

Guidelines available for use of plastic waste in road construction

- Indian Road Congress - IRC: SP:98-2013 - "Guidelines for the use of waste plastic in the hot bituminous mix (dry mixing) in wearing courses"
- Ministry of Road Transport and Highway – Manual for construction and supervision of bituminous work (Chapter 2.2.4 on polymer/Rubber modified bitumen)

3.2.1. Feedstock for Plastic to Road Technology:

According to IRC: SP: 98-2013 guidelines, the following types of waste plastic can be used in the construction of roads:

- Films (carry bags, cups) of thickness up to 60 microns (PE, PP and PS)
- Hard foams (PS), any thickness
- Soft foams (PE and PP), any thickness
- Laminated plastics of thickness up to 60 microns (including aluminium coated plastic), packing materials used for biscuits, chocolates, etc.

PVC should not be used for plastic to road as thermal degradation of PVC results in the emission of harmful gases like hydrochloric acid. Black coloured plastic waste is a result of repeated recycling and should not be used. Dust and other impurities should not exceed 1%[41].

3.2.2. Process of Utilising Plastic Waste for Road Construction

There are two processes available for using plastic waste in road construction:

- Dry Process: Addition of shredded plastic in hot aggregates to form Plastic Coated Aggregates (PCA)
- Wet process: Addition of waste plastic in the form of powder to hot bitumen

It is found that the wet process is not as cost-effective as the dry process and requires more investment and machinery, and that it is preferable to use the dry process in the construction of roads using plastic waste.

[41]Source: https://www.tce.edu/sites/default/files/PDF/IRC-Spec=Road-with-plastic-waste.pdf; Retrieved July, 2019

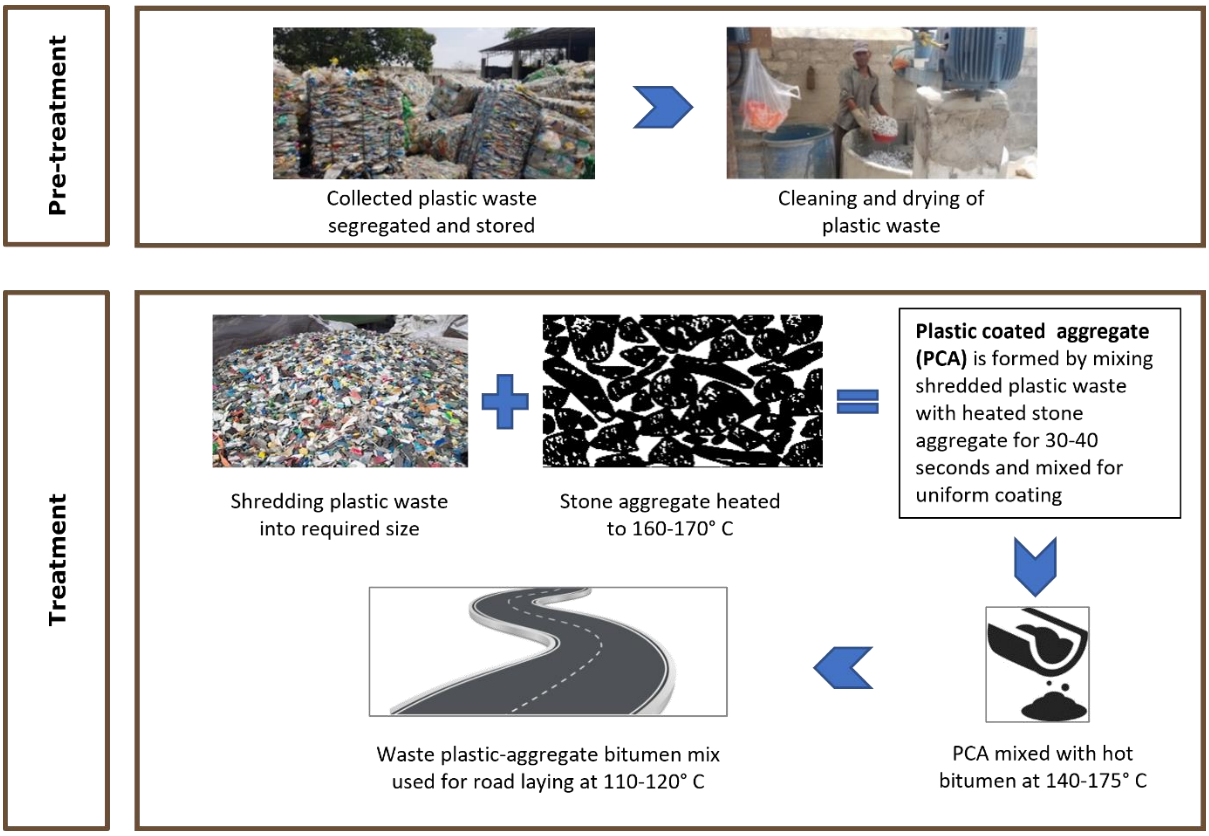

Figure 10: Schematic of plastic waste to road construction[42]

The waste plastic should be collected, segregated, cleaned, and then shredded.

Cleaning and Drying: The process starts with cleaning the plastic waste, which should be pre-sorted and de-dusted before use.

Shredding: *S*hredded waste plastic needs to conform to the size passing through a 2.36 mm sieve and retained on a 600 micron sieve to ensure better spreading and coating of the aggregate.

Mini Hot Mix Plant: The stone aggregate mix is transferred to the mix cylinder where it is heated to 165°C (as per IRC specification) and then transferred to the mixing puddler. While transferring the hot aggregate into the puddler, a calculated quantity of shredded plastics is sprayed over the hot aggregate within 30 seconds. The sprayed plastic films melt and coat the aggregate, thus forming an oily coating. Similarly, bitumen is heated to a maximum of 160°C in a separate chamber and kept ready. The temperature should be monitored to enable good binding and to prevent weak bonding. At the mixing puddler, the hot bitumen is added over the plastic-coated aggregate and the resulting mix is used for road construction. The road laying temperature is between 110°C to 120°C. The roller is normally of 8-tonne capacity.

[42]Adapted from: http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf, Retrieved September 15, 2019

Central Mixing Plant (CMP): For intensive works CMP can be used. The central mixing plant technique includes three materials[43]:

- **Materials I:** Hopper- generally filled with required aggregates as per the mix formula
- **Materials II**: Plastic films of not more than 60 micron thickness cut to a size less than 4 × 4 mm. This size needs to be ensured and must not be exceeded.
- **Materials III**: Bitumen of the type 60/70 or 80/100 to be used

Plastic waste is mixed with bitumen and heated to 140–175°C in the central mixing plant. The amount of plastic to be added is calculated as follows. Per minute spraying of plastic waste in terms of quantity is to be 10% that of per minute spraying of bitumen quantity. The requisite percentage of waste plastic to the weight of bitumen is injected with a pipe under compressed air into the drum of a mixing plant through a pipe at two-thirds the length of the drum or through an opening over the pug mill in the case of a batch mix plant[44]. The plastic waste is coated uniformly over the aggregate within 30–40 seconds, giving it an oily look. The plastic waste coated aggregate is mixed with hot bitumen and the resulting mix is used for road construction.

Performance evaluation of polymer coated bitumen road compared to normal bitumen road

As per the Performance Evaluation of Polymer Coated Bitumen Built Roads of the Central Pollution Control Board, plastic mixed roads have demonstrated a much higher performance compared to bitumen roads over time, and have developed no cracks or potholes. The roads, laid over various localities of Tamil Nadu, were exposed to various environmental conditions such as temperature and rainfall, and have demonstrated good performance.

Table 7: Comparison of various aspects of pavements constructed using bituminous concrete mixes with and without plastic waste[45]

Criteria	Bitumen Road	Plastic Modified Bituminous Road
Maintenance	5 years	Nil up to 10 years
Fatigue resistance (or Indirect Tensile Strength, MPa)	1.42	1.83
Rutting	Yes	No
Roughness	More bumps > 5200	Less bumps <4000
Stripping	5% in 24 hours	Nil if plastic is >6%
Moisture absorption	4%	0–2%

3.2.3. Environment Control

To avoid gaseous products causing air pollution, temperatures must be monitored during heating as plastic waste heated above 250°C may decompose. The IRC guidelines mention the impurity (dust)

[43] Source: http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf, Retrieved September 15, 2019

[44] Source: https://www.tce.edu/sites/default/files/PDF/IRC-Spec=Road-with-plastic-waste.pdf , Retrieved July, 2019

[45] Source: https://aphrdi.ap.gov.in/documents/Trainings@APHRDI/2017/4_Apr/Muncipal%20Waste%20Management/Kshitij%20Aditeya.pdf, Retrieved September 16, 2019

and melt flow test for plastic waste. The melting temperature of plastic waste should be maintained between 150 to 170°C to ensure that plastic boils but does not burn.

3.2.4. Advantages and limitations of Using Plastic Waste in Road Construction

Advantages	Limitations
• **Enhanced life and strength of road** Maintenance required after 10 years, compared to 5 years for normal roads (Knowledge Advisory Services and Consultancy Private Limited, 2014) • Enhanced resistance to extreme weather events • Increased binding and better bonding of the mix • Reduced CAPEX and OPEX (discussed below in detail) • Polystyrene and multi-layered plastics are also used in the processes, which are generally difficult to recycle	• Efficiency of the process depends on **cleaning and segregation of waste plastics** • Chemical additives and fillers in plastics may lead to **release of harmful gases** when heated at high temperatures or above melting temperatures of particular components • Due to road weathering over time, plastics particles generate micro-plastics and easily enter environment • Lack of control over process temperatures can lead to harmful gas release.

Plastic to Road in Bengaluru, India

Bruhat Bengaluru Mahanagara Palike (BBMP) has successfully laid 3,000 km of roads in Bangalore city by reusing 12,000 tonnes of non-recyclable plastic waste collected from the city's garbage. BBMP passed a resolution in 2006 promoting use of plastic admixtures in construction of all blacktop roads in the city and recommended a procurement price of processed plastic waste at 27 INR/kg. The rollout in Karnataka was undertaken in 3 year phases where 500 km of urban roads were paved using waste plastic as a binder. The funds for plastic to road construction were provided by BBMP.

A Memorandum of Understanding (MoU) was also signed between BBMP and KK Plastics where KK Plastic agreed to procure plastic waste from dry waste processing centres in the city at rate of 10 INR/kg. KK Plastics was also responsible for procuring, processing and delivering waste plastic to the Hot-Mix plant. BBMP also engaged with schools and colleges to generate awareness regarding the initiative[46].

Cost Saving from Using Plastic Waste in Bituminous Road Construction (1 km length, 3.75 m width)[47]

For New Construction of Roads	
• Cost of waste plastics: 7 INR/kg • Cost of processing: 5 INR/kg	*A. Total cost of Waste Plastics: 12 INR/kg*

[46] Source: https://aphrdi.ap.gov.in/documents/Trainings@APHRDI/2017/4_Apr/Muncipal%20Waste%20Management/Kshitij%20Aditeya.pdf, Retrieved September 16, 2019

[47] Source: http://www.ijirset.com/upload/2017/february/11_A%20Survey.pdf, Retrieved April 6, 2021

• Cost of Bitumen: 42 INR/kg • Bitumen use approx. 21,300 kg	*B. Cost of bitumen in new work: 8,94,600 INR/km*
• Waste plastic, co-processed with bitumen for PMB (8% by Wt.): 1,704 kg	*C. Cost of waste plastic used: 20,450 INR/km*
	D. Cost of Bitumen saved (1,704 kg, equivalent to plastic used): 71,550 INR/km
	Total Savings (D-C): 51,100 INR/km (798 USD/km)
For Upgradation of Roads	
• Cost of Bitumen: 42 INR/kg • Bitumen use approx. 11,925 kg	
• Waste plastic, co-processed with bitumen for PMB (8% by Wt.): 954 kg	*E. Cost of waste plastic used: 11,450 INR/km*
	F. Cost of Bitumen saved (954 kg, equivalent to plastic used): 40,050 INR/km
	Total savings (F-E): 28,600 INR/km (447 USD/km)

3.3. Plastic to Fuel

Plastic waste is composed of long polymer chains. The plastic to fuel (PTF) or pyrolysis process breaks down these chains in the absence of oxygen to produce compounds with shorter chains, followed by removal of any non-hydrocarbon atoms (e.g., oxygen, chlorine). This breakdown of long-chain polymers and formation of lower molecular weight fractions is called polymer degradation or de-polymerisation, the reverse of polymerisation.

The benefits presented by PTF technologies are twofold: (1) Transforming non-recyclable plastics into a valuable commodity, (2) Creating a reliable source of alternative energy from an abundant, no- or low-cost feedstock (4R Sustainability, 2011). However, the composition of plastic may vary and undesirable additives may pose a threat to the environment. Thus, types and compositions of plastics determine the pretreatment and entire process of conversion.

Pyrolysis is carried out at a temperature between 500 and 1,000°C and produces three-component streams: **Gas** (hydrogen, carbon monoxide, methane, carbon dioxide, and some hydrocarbons), **Liquids** (tar, pitch light oil and low boiling organic chemicals) and **Char**.

3.3.1. Feedstock for Pyrolysis

The ideal feedstock for pyrolysis depends on the intended end product. Many plastics, particularly polyolefin, which have high calorific values and simple chemical constitutions of primarily carbon and hydrogen, are usually used as the feedstock in pyrolysis. Pyrolysis of plastic waste is mainly influenced by **moisture content, fixed carbon, volatile matter, and ash content**. Plastic with high volatile matter can favour liquid oil production while plastic with high ash content decreases the production of liquid oil and increases the gaseous yield and char formation. Therefore, it is important to conduct a proximate analysis of the feedstock. PVC is not suitable for pyrolysis technology.

3.3.2. Pyrolysis Process

Pre-Processing: Depending on the structure of waste plastic, pre-treatment will be required to ensure smooth feeding into the system. The type of plastic used determines the processing rate as well as product yield, and contamination by undesirable substances and the presence of moisture increases energy consumption and promotes the formation of by-products in the fuel production process[48]. Plastic waste (preferably HD, LD, PP and multilayer packaging except PVC) is segregated and pre-treated. The segregated feedstock is shredded and the moisture content is reduced. Size reduction is an essential step in pre-treatment to ensure appropriate size of the feedstock in relation to the feed equipment of the furnace.

Pyrolysis: Pyrolysis is a fast-acting process resulting, in terms of content, in 50–70% oil, 10–30% char, and 15–20% syngas depending on the type of feedstock. A pyrolysis plant typically consists of three chambers; primary chamber, secondary chamber and conversion chamber. The pretreated feedstock is transferred to the primary chamber through a pump. In the primary and secondary chambers the plastic feedstock is purged with carbon dioxide, thereby pushing air to the top while the feedstock is transferred from the bottom to the next chamber, which ensures no oxygen is transferred into the reactor or conversion chamber.

The reactor is maintained at an elevated temperature (700°C or 900°C) in the presence of a catalyst to convert the plastics into gas and char. The conversion chamber has two exits, one each for the gas and char. The char (approximately 10% of the feed) is collected for disposal and the gas is passed into a condenser where it is cooled to 20°C and the pyrolysis oil separated out. The pyrolysis oil is filtered to 1 µm to remove deposits that could enter fuel lines and degrade the injection system. The figure below shows the layout of a pyrolysis plant.

Production of oil is dependent on the feedstock, temperature, pressure and time of retention in the reactor, and in terms of oil yield, research shows that the temperature and type of pyrolysis reactor play important roles. Further, use of catalysts enables temperatures to be lowered to 450^{o}C, increasing the yield. Effective temperature ranges and reactors for optimum production of oil for different types of plastics are tabulated in Annexure 2.

Distillation: The fuel in its vapour state is collected in the condensation chamber in the form of liquid fuel. This oil has properties similar to Low Diesel Oil (LDO) and can be used as an alternative to LDO in industry. Generally, 2 kg of waste plastic feedstock produces 1 litre of LDO. Figure 11 presents a schematic of the pyrolysis process.

[48]Source: https://wedocs.unep.org/bitstream/handle/20.500.11822/8638/WastePlasticsEST_Compendium_full.pdf?sequence=3&isAllowed=y, Retrieved September 16, 2019

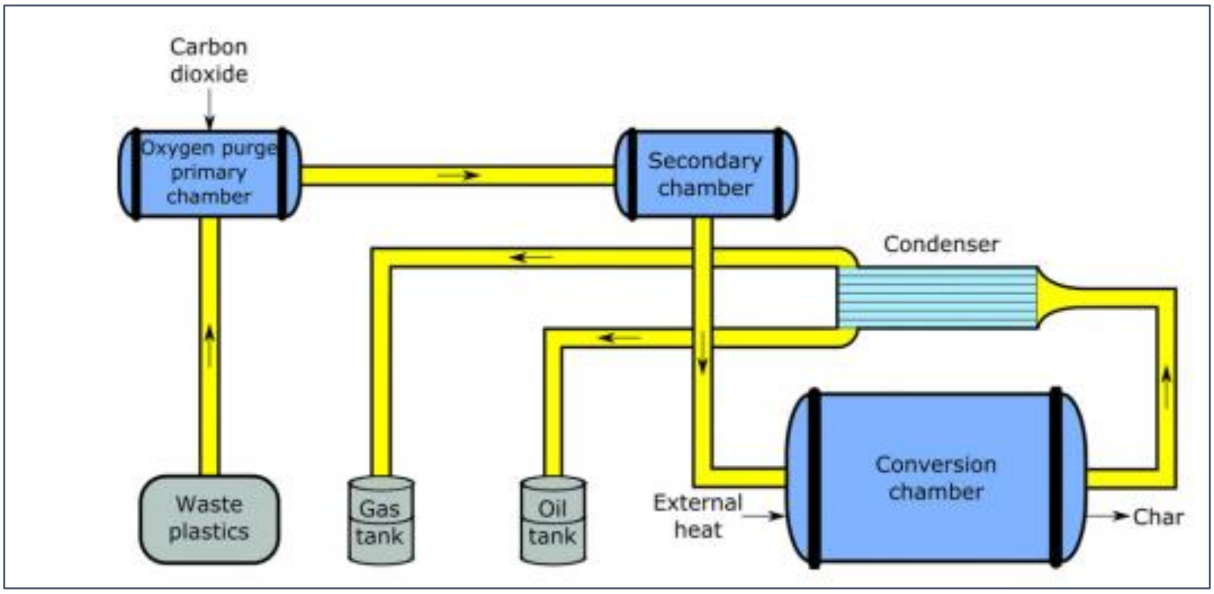

Figure 11: Schematics of a pyrolysis plant[49]

3.3.3. Operational Parameters

Operational factors that affect the process include the types of reactor, fluid, residence time, temperature and pressure of operation, experimental conditions and type of feedstock material. The most effective temperature for optimal liquid oil yield in plastic pyrolysis is in the range of 500–550°C for thermal pyrolysis. However, with the usage of catalysts the optimum temperature can be lowered to 450° C and a higher liquid yield obtained. The feedstock material also affects the product distribution and limits the operation in terms of time required for conversion and anticipated products. The purity of the feedstock material also influences the type and product distribution obtained by the pyrolysis of plastics. For example, higher amounts of PS, PP and LDPE results in higher yield. Table 8 below indicates the percentage of overall output from pyrolysis:

Table 8: Overall outputs from pyrolysis[50]

Output	Percentage of Overall Output
Char	Average of 2–3%
Natural Gas	Average of 8–10%
Fuel/Oil	Average of 80–90%

3.3.4. Environmental Control

Pyrolysis of plastic waste breaks down polymers into smaller molecules and sometimes monomer units and prevents the formation of harmful emissions such as COx, NOx, and SOx due to the absence of oxygen. The vapours or gases formed are generally cooled and condensed. Also, the non-condensable gases such as methane and hydrogen are generally co-fired with natural gas or propane to heat the vessels, resulting in CO2 and water. It is important to scientifically operate the pyrolysis

[49]Adapted from https://www.sciencedirect.com/science/article/pii/S0378382016307135, Retrieved May 5, 2021

[50] Source:http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf, Retrieved September 15, 2019

facility to avoid the production of dioxins. Vapours resulting from pyrolysis should be combusted at temperatures well above the destruction temperature of dioxins and furans.

3.3.5. Advantages and Limitations of the Pyrolysis Process

Advantages	Limitations
• Very useful, particularly for processing non-recyclable and low-grade plastic waste. Enables recycling of plastic laminates and multi-layer packaging, particularly, those with aluminium foils that are difficult to recycle using traditional recycling technologies. • Extremely high temperatures and an oxygen-starved environment ensure no emissions of harmful gases and toxins such as dioxins and furans. • Much lower carbon footprint compared to incineration	• Suitable for homogenous waste streams. PVC must reside in the feedstock to avoid the generation of toxins. • Highly energy-intensive process • Charcoal generated during the process may contain heavy metals, poly aromatic hydrocarbon (PAH) which can be hazardous in nature. Metals present in charcoal can result from additives in plastics and multilayer and laminated plastics. • Relatively high sulphur levels in end products • Necessitates monitoring of process fugitive emissions in work areas and emissions from engines/diesel generator sets (where this liquid fuel is used) for parameters such as CO, HCl, Styrene, Benzene, VOCs. • Melted plastic tends to stick to reactor walls and can block exits of volatile materials, necessitating regular reactor clearing and monitoring of pressures.

Pyrolysis in India

Though pyrolysis technologies are still in a nascent stage in India, some facilities are operating at a pilot scale.

Pyrolysis Plant in Pune[51]: Rudra Environmental Solutions was set up in 2010 to convert plastic waste to fuel. The collected plastic waste is shredded and put into a reactor. A catalyst is added and the plastic is heated at a temperature of 150°C. The gases emitted such as methane and propane are stored in a separate gas tank and used as a heating source for machine operation. The oil obtained is filtered, stored and prepared for dispatch. One tonne of plastic in the plant can be turned into approx. 600–650 litres of fuel, 20–25% synthetic gases and 5–10% residual char, which can be used as road filler with bitumen. The organisation currently collects plastic waste from nearly 15,000 households in Pune and encourages citizens throughout India to send plastic waste via courier for conversion to fuel. The organisation also has an arrangement to supply over 60 villages with poly-fuel at a rate of 36–38 INR per litre (0.50 USD/litre) as an alternative to kerosene,

[51] Source: https://swachhindia.ndtv.com/recycling-plastic-in-india-converting-plastic-waste-to-fuel-the-unrealised-potential-9436/, Retrieved December 12, 2020

with higher calorific value. Over a three-year period from 2015 to 2017 the plant processed more than 200 tonnes of plastic waste.

Pyrolysis Plant in Hyderabad: Pyrogreen Energy Private Ltd. designed, financed, commissioned and presently operates a 10 TPD pyrolysis plant in Pashamalyaram Industrial Area, located near Hyderabad city. Mixed waste is collected and passed through a drum-screen/trommel to remove impurities, shredded and then sent to a rotary dryer to remove moisture. The dried materials are fed into the pyrolyzer through a controlled feeding system where the material is processed under controlled conditions of temperature and pressure and in the absence of oxygen. A customized catalyst is added into the reactor vessel which prevents the formation of dioxins and furans during the process. The process yields fuel oil in gaseous form along with other gases. These vapourized gases are passed through heat exchangers, wherein the fuel oil gas is condensed into oil and the uncondensed gas is recycled for the heating system. Exhaust flue gases are then treated or scrubbed before release via a 15-m high chimney. During the pyrolysis process carbon ash is generated and collected through a closed ash collection system. Oil is passed through in-line filters and stored in an underground storage tank. The fuel produced has the following characteristics:

- High Calorific Value Fuel
- Low Sulphur Content
- High Flash Point
- Good Lubrication
- Specific gravity around 0.84

While furnace oil is produced directly from the system a distiller can also be installed to produce oil for use in a generator, which is sold at 35–36 INR/litre.

Figure 12: Pyrolysis Plant in Hyderabad (left), Distilled Furnace Oil Produced in Pyrolysis Plant (right)

Officials from Pyrogreen Energy Private Ltd. advise that a pyrolysis plant should be installed for a minimum 5 TPD capacity to ensure sustainability. The capital expenditure incurred is approximately 25 million INR (0.34 million USD); operational expenditure is determined by quantum of output (8 INR/litre of oil), transportation cost (2 INR/kg waste) and electricity cost[52].

[52] Discussion with Pyrogreen Energy Private Limited, Hyderabad, November, 2019

The Department of Municipal Administration, Government of Telangana, released a circular communicating to ULBs in the state to explore the possibility of handing over non-recyclable waste to Pyrogreen Energy Pvt. Ltd. for subsequent conversion into fuel oil or electricity, with transportation provided at no cost[53].

Pyrolysis in Japan: Case Example of Mogami Kiko

Mogami Kiko is the first plastic to oil company in Japan. This pyrolysis plant, with a capacity of 3 TPD, is located in a recycling complex in Shinjō city. The plant employs a fixed-bed, batch-pyrolysis system with a unit consisting two pyrolysis lines. The main pyrolysis vessels typically processes 1 TPD of plastics. External heating of the vessel is via combustion of the product oil or gas. Initial heating of the plastic wastes, containing PVC, at temperature of 400°C produces a hydrogen chloride-rich off-gas. This low-temperature pyrolysis gas, containing hydrogen chloride and hydrocarbons, is combusted and then cooled and scrubbed using an alkaline scrubbing solution to remove and collect the hydrogen chloride. After the primary de-chlorination process, conducted at a lower temperature, the evolved pyrolysis gases are directed away from the de-chlorination system and the temperature of pyrolysis is raised to 500°C. Pyrolysis of the main bulk of plastics then takes place over a period of 12–15 hours to produce medium and light oils and the non-condensed gases are flared. The product oil is partially fedback as fuel for the pyrolysis process.

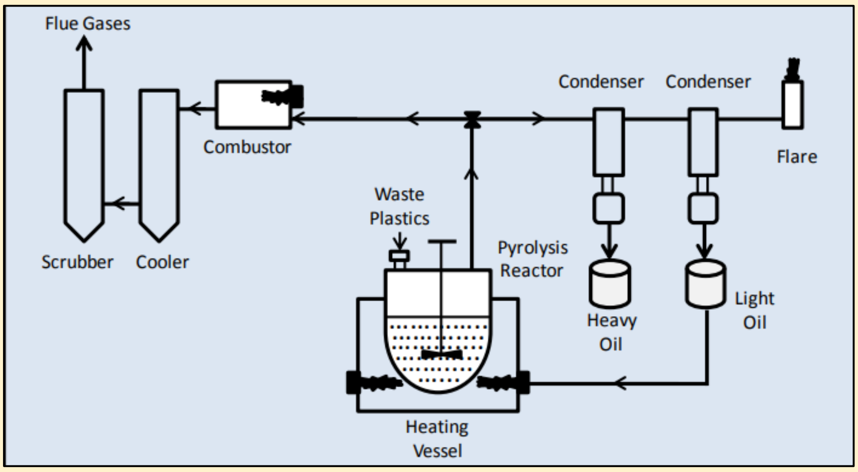

Figure 13: Pyrolysis Plant of Mogami-Kiko Co. Ltd., Yamagata, Japan[54]

Mixed plastic containers and packaging from household waste are thermally decomposed to produce 50–90% of hydrocarbon oil. When mixed plastics of bulk density 300 kg/cubic m is used as input, the performance of the plant is recorded to be 1.5 TPD per reactor[55].

[53] Source: https://emunicipal.telangana.gov.in/1/coir/Grid.aspx; Retrieved on 15May, 2021
[54] Source: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5aedb2351&appId=PPGMS, Retrieved May, 2021
[55] Source: https://wedocs.unep.org/bitstream/handle/20.500.11822/8638/WastePlasticsEST_Compendium_full.pdf?sequence=3&isAllowed=y, Retrieved September 16, 2019

Plasma pyrolysis

This is an advanced version of pyrolysis, which uses a plasma reactor to generate high temperatures (2760°C–7760°C) in an oxygen-starved environment to process plastic. The technology enables the disposal of all types of plastic and hazardous waste, including biomedical waste. The extreme conditions of the plasma kill stable bacteria such as *bacillus stearothermophilus* and *bacillus subtilis* immediately[56]. However, the viability and sustainability of this process require validation prior to applying for processing of municipal solid waste.

3.4. Gasification

Gasification is the thermal conversion of any hydrocarbon-based material, in the presence of limited amounts of air (oxygen), in a heated chamber into a mixture of combustible gases (hydrogen, carbon monoxide, carbon dioxide, methane and other trace compounds, termed syngas. Gasification of plastic waste is commonly carried out at high temperatures (>600˚C to 800˚C), and the syngas produced may have a heating value or net calorific value of 4–10 MJ/Nm^3 and can be further used as fuel for energy generation.

3.4.1. Feedstock for Gasification

Gasification provides flexibility with feedstock as it can potentially process both mixed waste and the plastic-only fraction of the waste. This makes gasification technology attractive. However, it is recommended to process only non-recyclable plastics through gasification due to the intensive energy requirements and to ensure maximum resource efficiency.

3.4.2. Gasification Process

Gasification is basically choked combustion in a staged manner, comprising a series of distinct thermal events combined to purposely convert solid organic matter into specific hydrocarbon gases as the output. The goal in gasification is to control the discrete thermal processes that usually occur simultaneously in combustion and re-organise them to achieve the desired end products[57].

A comparative analysis of thermal treatments of plastic waste is tabulated in Annexure 3.

In the gasification process, waste moves through three fundamental processors:

- In the first stage, the feedstock is moved into the **primary chamber** which is operated at below the stochiometric air requirement. Feedstock in the first chamber is semi-pyrolysed, resulting in the release of moisture and volatile components at temperatures below 600°C. The by-products of pyrolysis that are not vaporised are called char and consist mainly of fixed carbon and ash.

[56] Source: https://bvmengineering.ac.in/misc/docs/published-20papers/civilstruct/Civil/101017.pdf, Retrieved September 16, 2019
[57]Source: http://www.allpowerlabs.com/gasification-explained, Retrieved November 10, 2019

- The **secondary chamber** is operated under excess air conditions and is equipped with a conventional burner to maintain the operating temperature at all times. In the second gasification stage, the carbon remaining after pyrolysis is either reacted with steam or hydrogen or combusted with air or pure oxygen. Gasification with air results in a nitrogen-rich, low BTU fuel gas. Gasification with pure oxygen results in a higher quality mixture of carbon monoxide and hydrogen and virtually no nitrogen. Gasification with steam, or 'reforming', results in a hydrogen- and carbon dioxide-rich 'synthetic' gas (syngas). Typically, the exothermic reaction between carbon and oxygen provides the heat energy required to drive the pyrolysis and char gasification reactions.
- The main product obtained is a syngas, which contains carbon monoxide, hydrogen and methane. Typically, the gas generated from gasification will have a net calorific value of 4–10 MJ/Nm^3. The other main product produced by gasification is a solid residue of non-combustible materials (ash) containing a relatively low level of carbon.
- Syngas can be used in a boiler to generate steam for power generation or industrial heating, or as a fuel in a dedicated gas engine. After reforming it may also be suitable for use in a gas turbine. Syngas can also be used as a chemical feedstock.

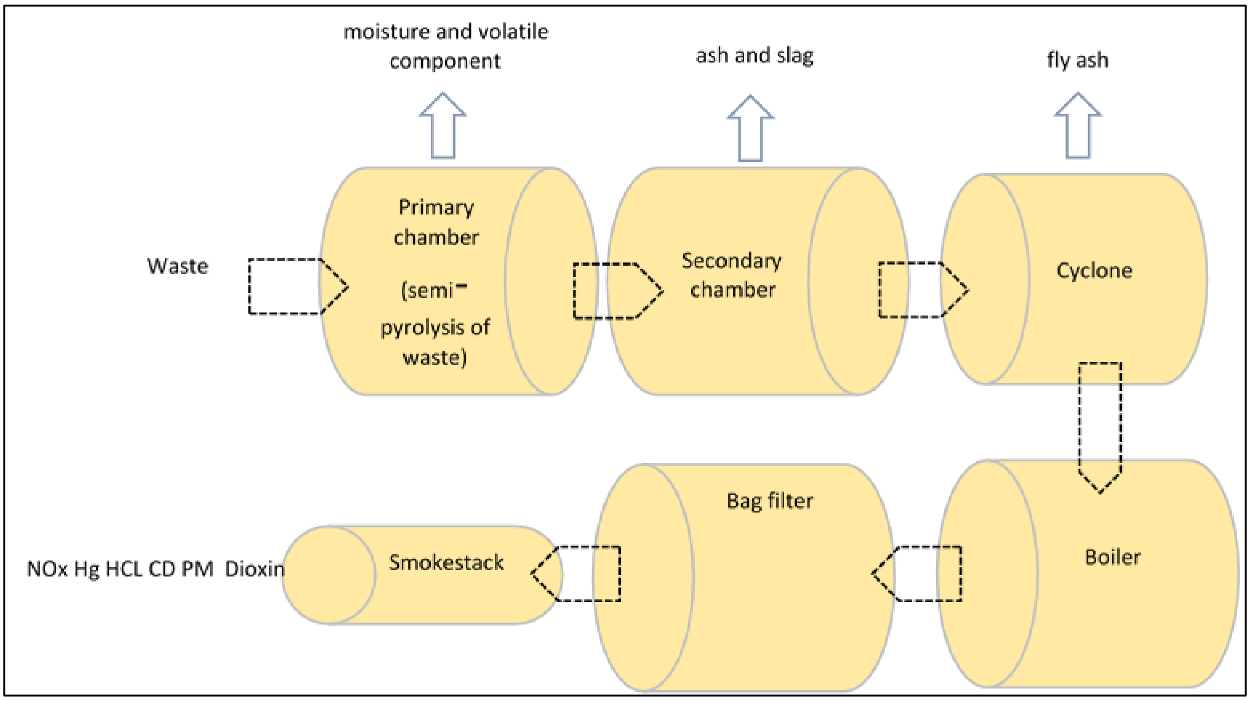

Figure 14: Schematic of a waste gasification plant

Types of Gasifiers

- **Fixed Bed Gasifiers** have a grate to support the feed material and maintain a stationary reaction zone. They are relatively easy to design and operate. The fixed bed gasifier has a bed of solid fuel particles through which the gasifying media and gas move either upward (called updraft), downward (called downdraft), or crossways (called cross draft)[58]. Details of the various types of movement in fixed bed gasifiers are given below[59]:

Updraft	Downdraft	Cross draft
Air is introduced from the bottom of the chamber and raises counter-current to the downward movement of the waste through the conversion zones. The gases produced move upwards and are removed from the top of the chamber. This upward movement of air and gases improves efficiency as the rising hot gases help to control temperatures, aid in drying of the feedstock, and improve the mixing of the gases in the chamber. Disadvantages of updraft systems are the possibility of tar in the raw gas and inefficient loading for some large or heterogeneous feedstocks.	Air is introduced at a midway point or top part of the chamber and syngas is removed from the bottom part of the chamber. Heat is added from the top of the chamber, and the gas temperature increases as it moves downward. The gas leaves the chamber at very high temperatures. This heat can be harnessed for use in heating the upper portion of the chamber. On exiting the chamber the gas must pass through the ash (in the form of char), which reduces the amount of tars in the syngas.	The air inlet and gas outlet are on opposite sides in the middle of the chamber. These types of gasifier are less common as they produce high temperature syngas at a high velocity that does not have as efficient CO2 reduction as other types of gasifier. The types of feedstock for these systems are limited by the system design to low ash fuels, such as wood, petroleum coke, and charcoal. Cross-draft gasifiers have several advantages, including high carbon monoxide, low hydrogen and low methane syngas content when used on dry fuels, and a fast startup time desirable for some applications.

- **Fluidised-bed Gasifiers** are a type of updraft gasifier and preferred for gasification as they can be used with multiple fuels, offer relatively compact combustion chambers and good operational control. In a fluidised bed boiler, a stream of gas (typically air or steam) is passed upwards through a bed of solid fuel and materials such as coarse sand or limestone. The gas acts as the fluidising medium and also provides the oxidant for combustion and tar cracking. Waste is introduced either on top of the bed through a feed chute or into the bed through an auger. The two main types of fluidised beds for power generation are bubbling and circulating fluidised beds.

A comparison of different reactors for gasification is tabulated in Annexure 4.

[58]Source: https://www.sciencedirect.com/topics/engineering/fixed-bed-gasifiers, Retrieved January 5, 2021
[59]Source: https://plastics.americanchemistry.com/Sustainability-Recycling/Energy-Recovery/Gasification-of-Non-Recycled-Plastics-from-Municipal-Solid-Waste-in-the-United-States.pdf, Retrieved January 5, 2021

3.4.3. Environmental Control

Process and emission control systems need to be properly designed to ensure health and safety requirements are met. The output products of gasification reactors can contain a variety of potential process and air pollutants that must be controlled prior to discharge into the ambient air. These include particulate matter, tars, nitrogen and sulphur oxides, dioxins and furans, hydrocarbons, and carbon monoxide. Different strategies can be adopted to control emissions from gasification processes, which are directly determined by the plant configuration adopted and, in particular, the specific requirements of the energy conversion device in question.

Air pollution control can be applied at the reactor outlet as well as exhaust gas outlet. The low levels of oxygen present in gasification processes strongly inhibit the formation of dioxins and furans, however hydrogen chloride in the syngas must be managed if combustion for heat or power follows gasification. Table 9 provides control standards for dioxins and furans, by country.

Table 9: Control standards for dioxin and furan, by country[60]

Organisation	Source	Standards for Dioxins and Furans
Hong Kong	Municipal Solid Waste Incinerator	13 ng/m3 (Total Mass)
United States of America	Municipal Solid Waste Incinerator (More than 35 Tonnes per day)	13 ng/m3 (Total Mass) about 0.1 to 0.3 ng I- TEQ/m^3
European Union	Waste Incinerator	0.1 ng I- TEQ/m^3
Japan	Waste Incinerator Capacity more than 4 Tonnes per hour Capacity from 2 to 4 Tonnes per hour Capacity less than 2 Tonnes per hour	 ng I- TEQ/m^3 ng I- TEQ/m^3 5.0 ng I- TEQ/m^3
Canada	All Incinerators	0.08 ng I- TEQ/m^3
India	Bio-medical Waste Incinerator	0.1 ng TEQ/Nm^3 (at 11% O2)

The management of solid residues, i.e., bottom ash and APC residues (that include the fly ash) is crucial, and the type and composition of these residues is mainly determined by the specific gasification technology as well as types of treated wastes. Fly ash should be treated before being disposed of in landfills.

3.4.4. Advantages and Limitations of the Gasification Process

Advantages	Limitations
• Syngas generated by gasification is easier to handle, meter, control and burn. • Gasification plants can be designed for small to medium scale, thereby being economical in comparison to direct combustion plants.	• Gasification facilities require air pollution control and monitoring equipment which is not generally found in smaller units. • Cleaning of syngas is an energy intensive process and costly. • Syngas is toxic and potentially explosive; it requires major security and reliable control systems.

[60] Source: http://www.cpcbenvis.nic.in/cpcb_newsletter/Dioxin.pdf, Retrieved December 20, 2019

• Gasification results in improved quality of solid residues and greatly reduced generation of pollutants like dioxins, furans and NOx. • Syngas can be used, after treatment, in highly efficient internally-fired cycles.	• The actual production of pollutants depends on how syngas is processed; if the syngas is eventually oxidised, along with dioxins, furans and NOx, the process may still pose a potential threat. • Gasification is a complex process and difficult to operate and maintain.

Commercial plant for liquid and gaseous fuel production in Japan

Gasification technology allows waste to be thermally decomposed resulting in the generation of fuel gas with a high caloric value. The plant at Iwaki, developed by CR-POWER LLC (formerly OSTRAND Corp), Tekken Corporation and East Nippon Expressway Company Ltd. (NEXCO), was initially developed as a demonstration project for gasification using biomass. Since 2015 the plant has been used for commercial application by NEXCO. The plant's features include[61]:

- Feed: All plastics (thermoplastics, thermosets, halogen containing); plastics contained with biomass, metal, asbestos etc.; biomass
- Treatment Capacity: 200 kg/hour
- Operating conditions: Temperature of 700°C
- Utility: Power (5.7 kWh/h), Nitrogen gas (20 Nm^3/h) and chilled water (50 L/h).

Typically the outputs from the plant consist of:

- Gaseous products: 80–100 Nm^3/h; 5,000–6,000 kcal/Nm^3
- Tar: 30–40 kg/h
- Char: 20–30 kg/h

Advantages of this technology:

- MSW of 5 TPD is sufficient to operate a plant
- As it follows a thermal chemical reaction in non-oxidized environment, no harmful substance such as Dioxins, NOx and SOx are generated
- Higher power generation efficiency of around 40%
- Semi-skilled staff operational requirement

Gasification plants typically consist of a hopper, feeder, rotary reactor, condenser, gas refiner, oil (gas) storage tank and dual fuel engine generator, as below:

[61] Source: https://wedocs.unep.org/bitstream/handle/20.500.11822/8638/WastePlasticsEST_Compendium_full.pdf?sequence=3&isAllowed=y, Retrieved September 16, 2019

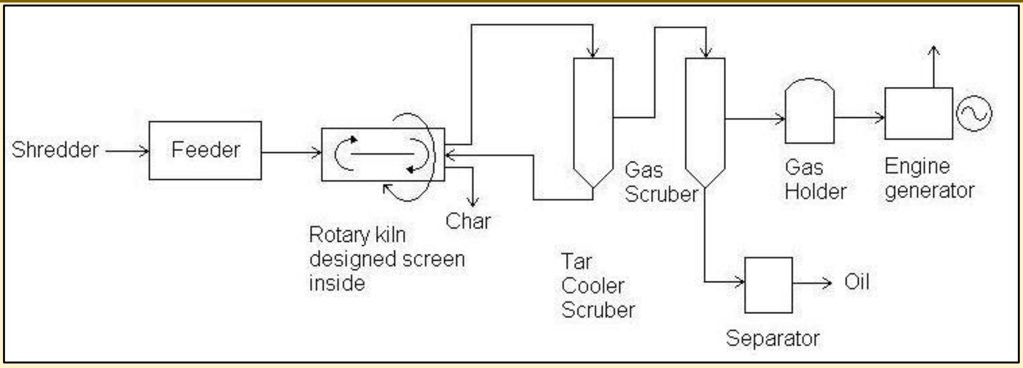

Figure 15: Schematic diagram of a typical gasification plant in Japan[62]

3.5. Co-processing of Plastic Waste in Cement Kilns and Power Plants

The SWM Rules, 2016 define co-processing as the use of non-biodegradable and non-recyclable solid waste having a calorific value exceeding 1,500 kcal as raw material or as a source of energy or both to replace or supplement natural mineral resources and fossil fuels in industrial processes. The Rules also define Refused Derived Fuel (RDF) as a fuel derived from the combustible waste fraction of solid waste such as plastic, wood, pulp or organic waste, other than chlorinated materials, in the form of pellets or fluff produced by drying, shredding, dehydrating and compacting solid waste. This material can be utilised for co-processing in various industries such as cement and thermal power plants.

3.5.1. Feedstock for Co-processing

According to the Basel Convention, hazardous waste can be disposed of in an environmentally safe and sound manner through the technology of co-processing in a cement kiln. CPCB has also approved coprocessing of plastic waste in cement factories as an environmentally sound technology. The Guidelines on Usage of Refuse Derived Fuel in Various Industries by MOHUA categorise Segregated Combustible Fraction (SCF) and RDF into four types based on their usage (detailed characteristics are tabulated in Annexure 5):

- **SCF:** Input material with calorific value exceeding 1,500 kcal to be used for Waste to Energy plant or RDF pre-processing facility
- **RDF Grade III:** Input material with calorific value exceeding 300 kcal to be used for co-processing directly or after processing with other waste materials in cement kiln
- **RDF Grade II**: For direct co-processing in cement kiln and with calorific value exceeding 3,750 kcal
- **RDF Grade I:** For direct co-processing in cement kiln and with calorific value exceeding 4,500 kcal

[62] Source: http://www.unido.or.jp/en/technology_db/1643/, Retrieved May 3, 2021

According to European Standard EN 15339 solid recovered fuel- specification and class, SRF/RDF should have the following technical and environmental specifications. The most desirable attributes are class 1; desirability drops with higher-rated classes.

Table 10: European Standard for Solid Recovered Fuel (or RDF) Specification and Class[63]

Classification Property	Unit	Class 1	Class 2	Class 3	Class 4	Class 5
Net Calorific Value	MJ/kg (mean	≥25	≥20	≥15	≥10	≥6.5
Moisture content	% wt/wt (mean)	≤10	≤15	≤20	≤30	<40
Chlorine content (dry)	% wt/wt (mean)	≤0.2	≤0.6	≤0.8	-	-
Ash content (dry)	% wt/wt (mean)	≤10	≤20	≤30	≤40	<50
Mercury (Hg) (as received)	mg/MJ (Median	≤0.02	≤0.03	≤0.06	-	-
	mg/MJ (80th percentile	≤0.04	≤0.06	≤0.06	-	-

3.5.2. Feeding Process of Co-processing

Cement plants should have a separate feeding arrangement for undertaking co-processing of Alternative Fuel and Raw Materials (AFRs). If one is already present on the calciner or kiln inlet, the same can be utilised for plastics as well; otherwise, a new feed arrangement needs to be set up. Feeding facilities consist of completely covered storage along with a conveying mechanism to move plastic waste from the storage area to the kiln either manually or automatically. Manual means consist of a winch and hopper arrangement and conveyor belts. At the feed point, equipment such as double flap valves, shut off gates are preferably installed to ensure uniform feeding and safety in operation. The feeding facility shall also be equipped with a lab to carry out analysis of calorific value, ash content, moisture content and chloride content.

Feeding of plastic waste should take place only after the kiln attains stable operating conditions (temperature: 850°C to 1,800°C). The different feed points for plastic waste materials in cement production are:

- Main burner at the rotary kiln outlet end
- Rotary kiln inlet end
- Pre-calciner
- Mid-kiln (for long dry and wet kilns)

[63] Source: http://www.wrap.org.uk/sites/files/wrap/WDF_Classification_6P%20pdf.pdf, Retrieved January, 2021

The feed points are selected depending on the feedstock. Plastic waste contaminated with toxins such as pesticides should be fed in the main burner to ensure complete combustion at high temperature over a long retention time. However, it should be ensured that plastics are shredded to less than 20 mm size before being fed to the main burner. Non-recyclable uncontaminated plastics can be fed at the other feed points such as calciner, kiln inlet or mid-kiln. The figure below presents the co-processing of plastic waste in cement kilns.

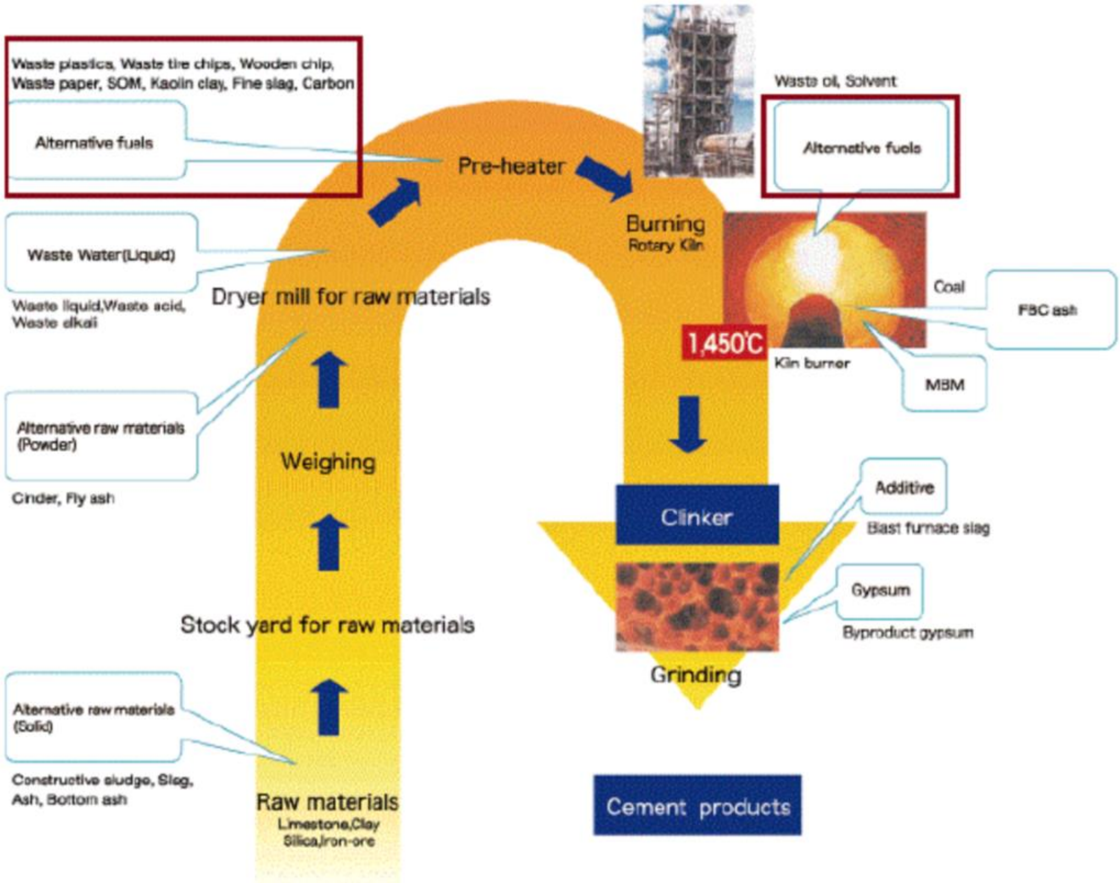

Figure 16: Process flow diagram for co-processing of plastic waste in cement kilns[64]

3.5.3. Environment Control Measures for Co-processing Waste in Cement Kiln

The Environment (Protection) Third Amendment Rules, 2016 by the Ministry of Environment Forest and Climate Change (MOEFCC) provides emission standards and guidelines for cement industries with co-processing of waste. Feeding of plastic waste should not be continued if the Continuous Emission Monitoring System (CEMS) is not connected with CPCB and SPCB servers or emission values are not in compliance with the prescribed emission standards, as indicated in the table below.

[64] Source: https://cpcb.nic.in/uploads/plasticwaste/Co-processing_Guidelines_Final_23.05.17.pdf, Retrieved September 16, 2019

Table 11: Emission standard and guidelines for cement plant with co-processing of waste[65]

Sl. No.	Parameter		Concentration not to exceed, in mg/Nm^3	Monitoring frequency
1	Particulate Matter (PM) or dust	Anywhere in the Country	30	Continuously
		Critically polluted area or urban centres with populations of 1.0 lakh or within periphery of 5.0 km radius	30	
		Other than critically polluted area or urban centre	30	
2	SO2		100, 700 and 1000 based on pyrite; sulphur in limestone is below 0.25%, 0.25–0.5% and over 0.5% respectively.	Continuously
3	NOx		600	Continuously
4	HCl		10 mg/Nm^3	Once yearly
5	Sb+As+Pb+Co+Cr+Cu+ Mn+Ni+V and their compounds		0.5 mg/Nm^3	Once yearly
6	Total Organic Carbon (TOC)		10 mg/Nm^3	Once yearly
7	HF		1 mg/Nm^3	Once yearly
8	Hg and its components		0.05 mg/Nm^3	Once yearly
9	Dioxins and Furans		0.1 ngTEQ/Nm^3	Once yearly
10	Particulate matter from raw mill, kiln and pre-calciner system combined		0.125 kg/tonne of clinker	

Apart from gaseous emission, these guidelines also delineate standards for wastewater discharge. Storm water shall not be allowed to mix with effluent, treated sewage, scrubber water and/or floor

[65] Source: http://ismenvis.nic.in/Database/Notification_10th_May_2016-GSR497E_12779.aspx, Retrieved September 16, 2019

washings. Storm water within site boundaries of industries shall be channelised through separate drains. Further, scrubbers meant for scrubbing emissions shall not be used as quenchers.

The following standards (Table 12) should be maintained by the plant while discharging service wastewater.

Table 12: Standards to be maintained for discharge of wastewater by co-processing facility[66]

Particular	Concentration not to exceed (milligrams/litre) (except pH and temperature)
pH	5.5 to 9.0
Suspended Solids	100
Oil and Grease	10
Temperature	Not more than 5°C higher than intake water temperature

Indicative Capital and Operational Costs for Co-Processing of RDF in India

The overall cost of RDF for co-processing depends on factors such as pre-processing, transportation, feeding mechanism and its modifications, monitoring of emissions and the quality of cement envisaged. Moreover, different grades of RDF will have different calorific values, and hence the cost will fluctuate. As per the Guidelines on Usage of Refuse Derived Fuel in Various Industries (2018), the commercial acceptability of properly processed RDF is agreed at 0.4 INR per 1,000 kcal/kg (0.0054 USD per kcal/kg).

The capital costs and operation and maintenance costs for co-processing of RDF include:

- Capital cost for setting up RDF Plant
- Capital cost for storage and feeding mechanism (retrofitting) of RDF at cement plant
- Operational costs for RDF production
- Transportation of RDF to cement plants/waste to energy plant
- Operational cost for using RDF at cement plant/waste to energy plant

Table below gives indicative Capital, Operation and Maintenance costs of RDF Plants of various capacities in India[67]. The cost is further segregated to provide for different grades of RDF.

Parameter	Up to 100 TPD	100–200 TPD	200–300 TPD
Capital Cost (RDF 25 mm)	153 million	341.91 million	447.69 million
Capital Cost (RDF 50 mm)	125.4 million	215.58 million	295.25 million
Operation & Maintenance Cost (RDF 25 mm)	1,390 per tonne	1,870 per tonne	1,851 per tonne

[66] Source: http://ismenvis.nic.in/Database/Notification_10th_May_2016-GSR497E_12779.aspx, Retrieved September 16, 2019

[67] Source: http://164.100.228.143:8080/sbm/content/writereaddata/Guidelines%20on%20RDF%20Usage.pdf, Retrieved September 16, 2019

Operation & Maintenance Cost (RDF 50 mm)	1,150 per tonne	1,200 per tonne	1,280 per tonne
Transportation Cost for 100 Km per tonne (@3 INR per Km). However, the cost of transportation decreases with increase in distance and reverse haulage options.			

(1 USD = 72.55 INR)

3.5.4. Advantages and limitations of Co-Processing of Plastic Waste in Cement Kilns

Advantages	Limitations
• Co-processing of plastic waste in cement plants is accepted internationally (e.g., by Basel Convention for disposal of hazardous waste; disposal of POPs [Persistent Organic Pollutants] by the Montreal protocol); CPCB has also approved co-processing of plastic waste in cement factories as an environmentally sound technology • High temperature of 1,400°C and residence time of 4–5 seconds in oxygen rich atmosphere ensure complete combustion of plastic feedstock • Calorific value of around 3,000 kcal provides sufficient thermal energy for operation of these plants, reducing dependency on non-renewable fossil fuel • RDF acts as an alternative to landfill, thereby leading to conservation and reduction in greenhouse gas emissions • Acidic gases generated in combustion process are neutralised by alkaline raw material in cement kiln and incorporated into cement clinker in a near-irreversible manner; no additional waste is generated.	• Technological changes required to make plastic waste/RDF suitable for usage (for e.g., shredding to required size) • Continued supply of fuels is key to ongoing operations at cement plants, requiring construction of storage facilities for RDF at cement plants and attention to associated fire hazards • For urban local bodies, feasibility and cost-effectiveness of co-processing technology depend on distance of cement industry from the city

Co-processing of plastic waste in cement plants in India

ACC Ltd. is a pioneer in installing and providing co-processing facilities under the brand name of Geocycle, which is also the global waste management brand of Lafarge-Holcim, the promoter of ACC Ltd. Lafarge-Holcim is a world leader in cement manufacturing and has over 30 years' experience in waste co-processing.

In India, Geocycle has set up 14 co-processing facilities and 6 dedicated pre- processing facilities for handling large volumes and various kinds of waste including MSW-based RDF. The Kymore Plant in

Madhya Pradesh has the capacity to utilize 350 TPD of alternative fuel[68]. The plant currently receives the segregated combustible fraction of municipal solid waste from Katni, Satna and Jabalpur. Other types of waste include biomass and hazardous waste from pharma, automobile, manufacturing/engineering, refinery, chemical, textile and beverage sectors and other non-hazardous wastes such as FMCG. The plant is modern, equipped with the latest equipment sourced worldwide, and has installed a sophisticated firefighting system. A shredding line of 200 m^3/hr (90,000 TPA) capacity and proper storage and processing shed is in place. The plant's laboratory tests samples from each truckload of MSW fraction for moisture, chlorine, ash, calorific value prior to waste processing. Studies show that the co-processing used has no undesirable impact on the environment, clinker or cement properties. A research study also indicates that co-processing at Kymore Plant helps in diverting 9 tonnes of coal per day and a cost saving of approximately 9,705 INR/day (130.85 USD/day). The co-processing method has also helped reduce overall CO_2 emissions, with the reduction estimated at 17.81 tonnes/day[69].

Alternative Fuel Substitution in Japan

In Japan, substitution of conventional fuel with alternative fuel at a rate of 15% has been practiced to date, which goes beyond the 10% requirement given in the Cement Sustainability Initiative Guidelines[70]. Two types of plastic waste are used as substitute fuel: Refuse Derived Fuel (RDF), also called Solid Recovered Fuel (SRF) and Refuse Derived Paper and Plastic Densified Fuel (RPF). Heating values of solid RDF and RPF depend on the composition of the input feed. Typical heating values of RDF and RPF are:

- RDF: 4,000–5,000 kcal/kg
- RPF: 6,000–8,000 kcal/kg

Earthtechnica is one of the companies operating solid fuel production plants at commercial scale in Japan. The plant uses waste plastics, used paper and waste wood as substitutes for coal and heavy oil. This system effectively converts waste plastics of low specific gravity such as films and sheets into solid fuel suitable for various solid fuel boilers. The plant comprises the following facilities:

- Multirotor primary and secondary crushers with large hoppers suitable for bulky feedstock.
- Airjet Separator to remove heavy impurities such as iron fragments
- Multi Sorter to detect PVCs and PVDCs, lowering the chlorine content of the feedstock
- Multi Press to prepare pellets using frictional heat inside the ring-die without requiring external heating
- Pellet cooler to cool the solid fuel to room temperature using air

[68] Source: http://164.100.228.143:8080/sbm/content/writereaddata/Guidelines%20on%20RDF%20Usage.pdf, Retrieved September 16, 2019
[69] Source: https://www.ijrdet.com/files/Volume4Issue9/IJRDET_0915_08.pdf, Retrieved May 3, 2021
[70] Source: https://www.ifc.org/wps/wcm/connect/33180042-b8c1-4797-ac82-cd5167689d39/Alternative_Fuels_08+04.pdf?MOD=AJPERES&CVID=lT3Bm3Z , Retrieved April 5, 2021

It is estimated that for every tonne of plastic waste used, fossil fuels corresponding to 17 to 42 GJ can be saved, depending on the waste constituents[71]. Cement companies in Japan are investing to use more plastic waste as fuel to produce cement. Taiheiyo Cement plans to employ new technology for using plastic in an efficient coal making process and deploy dedicated equipment at nine factories across the country. Meanwhile, Sumitomo Osaka Cement is investing 93.6 m USD in environmental efforts, including handling plastic waste, by financial year 2022. In fiscal 2017, the company accepted 5.64 million metric tonnes of waste materials and by-products.

These initiatives involving use of plastic waste for co-processing in cement plants are reflected in the 0.6 million tonne reduction in exports of plastic waste from Japan over two years (2017–2019)[72].

[71] Source: http://www.iipinetwork.org/wp-content/Ietd/content/use-waste-plastics-fuel.html, Retrieved April 5, 2021
[72] Source: https://www.cemnet.com/News/story/169254/japanese-cement-producers-help-reduce-plastic-waste.html, Retrieved April 5, 2021

4. Annexures

Annexure 1: Types of Air Filter[73]

Type	Filtering Efficiency	Advantages	Limitations
Fabric Filter	Up to 99.9%	Efficiency rises with increased dust cake buildup on fabric	Flow resistance increases with dust buildup; abrasives cause wear
Cyclone	Depends on particle size; 5 µm particles: 50% 8 µm particles: 100%	Efficient for large particles; involves minimal pressure drop	Less effective for smaller particles
Electrostatic precipitator	1 to 50 µm: 80 to 99% 5 to 10 µm: 99%+	Effective under high temperature and corrosive conditions	High cost; large size of equipment; requirement for specialist maintenance
Wet scrubber	>5 µm: 96% 1 to 5 µm: 20 to 80%	Effective with hot gases, corrosives; eliminates explosion hazards	Noise; corrosion; biological fouling (not an issue in caustic or acid scrubbers)
Packed tower Scrubber	High-level surface contact for reaction	Effective for water miscible/soluble materials	Noise; corrosion; biological fouling (not an issue in caustic or acid scrubbers)
Air cleaner (thermal oxidation, incineration or flare)	For gases or vapours	Effective at destroying gases and vapours	Not suitable for solids

[73] Source: https://www.hsa.ie/eng/Publications_and_Forms/Publications/Occupational_Health/Local_Exhaust_Ventilation_LEV_Guidance.pdf, Retrieved December 20, 2019

Annexure 2: Effective temperature range and reactors for optimum production of oil[74]

Type of Plastic	Reactor	Process Parameters				Yield			Remarks
		Temperature (°C)	Pressure	Heat rate (°C/m)	Duration (minutes)	Oil (wt%)	Gas (wt%)	Solid (wt%)	
PET	Fixed Bed	500	-	10	-	23.1	76.9	0	-
	-	500	1 atm	6	-	38.29	52.13	8.98	-
HDPE	Horizontal Steel	350	-	20	30	80.88	17.24	1.88	Stirring rate 200 RPM; FCC catalyst 10 wt%
	Semi Batch	400	1 atm	7	-	82	16	2	Stirring rate 50 RPM; FCC catalyst 20 wt%
	Batch	450	-	-	60	74.5	5.8	19.7	-
	Semi Batch	450	1 atm	25	-	91.2	4.1	4.7	-
	Fluidised Bed	500	-	-	60	85	10	5	-
	Batch	550	-	5	-	84.7	16.3	0	-
	Fluidised Bed	650	-	-	20-25	68.5	31.5	0	--

[74] Source: https://www.sciencedirect.com/science/article/abs/pii/S0196890416300619#:~:text=The%20pyrolysis%20temperatures%20were%20within,product%20yield%20(80.88%20wt%25), Retrieved December 20, 2019

Type of Plastic	Reactor	Process Parameters				Yield			Remarks
		Temperature (°C)	Pressure	Heat rate (°C/m)	Duration (minutes)	Oil (wt%)	Gas (wt%)	Solid (wt%)	
PVC	Fixed Bed	500	-	10	-	12.3	87.7	0	Also yields HCl: 58.2 wt%
	Fixed Bed	520	2 KPa	10	-	12.79	0.34	28.13	-
LDPE	Pressurized Batch	425	0.8–4.3 Mpa	10	60	89.5	10	0.5	-
	Batch	430	-	3	-	75.6	8.2	7.5	Also yields wax = 8.7 wt%
	-	500	1 atm	6	-	80.41	19.43	0.16	-
	Fixed Bed	500	-	10	20	95	5	0	-
	Batch	550	-	5	-	93.1	14.6	0	-
	Fluidised Batch	600	1 atm	-	-	51.0	24.2	0	Also yields wax: 24.8 wt%
PP	Horizontal Steel	300	-	20	30	69.82	28.86	1.34	-
	Batch	380	1 atm	3	-	80.1	6.6	13.3	-
	Semi Batch	400	1 atm	7	-	85	13	2	Stirring rate 200 RPM; uses FCC catalyst 10 wt%
	Semi Batch	450	1 atm	25	-	92.3	4.1	3.6	Stirring rate 50 RPM; uses FCC catalyst 10 wt%
	-	500	1 atm	6	-	82.12	17.76	0.12	-

Type of Plastic	Reactor	Process Parameters				Yield			Remarks
		Temperature (°C)	Pressure	Heat rate (°C/m)	Duration (minutes)	Oil (wt%)	Gas (wt%)	Solid (wt%)	
	Batch	740	-	-	-	48.80	49.6	1.6	-
PS	Semi Batch	400	1 atm	7	-	90	6	4	Stirring rate 200 RPM; uses FCC catalyst, cat/poly: 10 w/w
	Pressurized Batch	425	0.31–0.61 Mpa	10	60	97	2.50	0.5	Uses Zn catalyst, cat/poly: 5 w/w
	Batch	500	-	-	150	96.73	3.27	0	64.9 wt% of liquid comprised of styrene
	Batch	581	-	-	-	89.5	9.9	0.6	-

Annexure 3: Comparative analysis of thermal treatments of plastic waste[75]

	Combustion	**Gasification**	**Pyrolysis**
Objective	To maximize waste conversion to high temperature flue gases, mainly CO2 and H2O	To maximize waste conversion to high heating value fuel gases, mainly CO, H2 and CH4	To maximise thermal decomposition of solid waste to gases and condensed phases
Reaction Environment	Oxidising (oxidant amount larger than that required by stoichiometric combustion)	Reducing (oxidant amount lower than required by stoichiometric combustion)	Total absence of any oxidant
Reactant gas	Air	Air, pure oxygen, oxygen-enriched air, steam	None
Temperature	Between 850°C and 1,200°C	Between 550°C and 900°C (air gasification) and 1,000°C to 1,600°C for oxygen enriched air	Between 500°C and 800°C
Pressure	Generally atmospheric	Generally atmospheric	Slight over-pressure
Produced gases	CO_2, H_2O	CO, H2, CO2, H2O, CH4	CO, H2, CH4 and other hydrocarbons
Pollutants	SO2, NO_x, HCl, PCDD/F, particulates	H2S, HCl, CO, NH3, HCN, tar, alkali, particulates	H2S, HCl, NH3, HCN, tar, particulates
Ash	Bottom ash can be treated to recover ferrous (iron, steel) and non-ferrous metals (e.g., aluminium, copper, zinc) and inert materials (to be utilized as sustainable building materials); air pollution control residues are generally treated and disposed of as industrial waste	Same as at left/Combustion; bottom ash often produced as vitreous slag, utilizable as backfilling material in road construction	Often has high carbon content; treated and disposed of as industrial special waste
Gas cleaning	Treated in air pollution control units to meet emission limits and returned to the stack	Syngas can be cleaned to meet standards in chemicals production processes or high efficiency energy conversion devices	Syngas can be cleaned to meet standards in chemicals production processes or high efficiency energy conversion devices

[75] Source: http://energy.cleartheair.org.hk/wp-content/uploads/2016/05/Arena2012-SWGasification-Review.pdf, Retrieved December 20, 2019

Annexure 4: Comparison between different reactors for gasification[76]

Parameters	Downdraft Fixed Bed	Updraft Fixed Bed	Bubbling Fluidised Bed	Circulating Fluidised Bed	Rotatory Kiln	Moving Grate	Plasma
Particle size	Waste particle diameter up to 100 mm; poor temperature control leads to risk of sintering	Waste particle diameter up to 100 mm; poor temperature control leads to risk of sintering	No waste particles exceeding 150 mm; bed particle diameter 0.08–3.0 mm; attrition of bed particles (and their entrainment) may be severe	No waste particles exceeding 100 mm; bed particle diameter 0.05–0.5 mm	No size restrictions; any size treatable from fines to large lumps	No particles exceeding 200 mm	No size restrictions
Morphology	Uniform	Mostly uniform	Uniform	Uniform	Not an issue	Not an issue	Not an issue
Moisture content	<20%	<50%	<55%	<55%	Not an issue	<60%	Not an issue
Ash content	<5%	<15%	<25%	<25%	<40%	<20%	Not an issue
Ash meting point	>1,250°C	>1,000°C	>1,000°C	>1,000°C	Not an issue	>1,200°C	Not an issue

[76] Source: http://energy.cleartheair.org.hk/wp-content/uploads/2016/05/Arena2012-SWGasification-Review.pdf, Retrieved December 20, 2019

Parameters	Downdraft Fixed Bed	Updraft Fixed Bed	Bubbling Fluidised Bed	Circulating Fluidised Bed	Rotatory Kiln	Moving Grate	Plasma
Temperature profile	Large temperature gradients can occur; hot spots frequent	Large temperature gradients; hot spots frequent; relatively low gas exit temperatures	Temperature mostly constant in vertical direction; very small variation in radial direction; Range: 550–1,000°C	Small temperature gradients in direction of solids flow, avoidable if high solid flow circulation rate used; Range: 900–1000°C	Longitudinal/ transversal gradient may be large and not easily controlled	Longitudinal/ transversal gradients present	Determined by specific process, but usually very high, typically 1,500–5,500°C
Residence time	Particles remain in bed until discharged	Particles remain in bed until discharged	Particles present for substantial time (minutes to hours) in bed; gas residence time depends on gas velocity, which is below 2 m/s	Particles pass repeatedly through circulation loop, residence time for each circuit is few seconds; gas velocity is 3–15 m/s	Very long (1–2 hours)	Longer (>1 hour) than for combustion process	NA

Parameters	**Downdraft Fixed Bed**	**Updraft Fixed Bed**	**Bubbling Fluidised Bed**	**Circulating Fluidised Bed**	**Rotatory Kiln**	**Moving Grate**	**Plasma**
Conversion	Very high conversion attainable with use of gas plug flow and adequate temperature control	High gasification efficiency	Mixing of solids and gas bypassing can result in lower performance than other reactors	High conversion possible	High conversion attainable	>90% conversion efficiency attainable	100% conversion attainable
Process flexibility	Very limited; any change in process variables often requires new reactor design	Very limited; any change in process variables often requires new reactor design	Excellent; can be used for low- and high-temperature pyrolysis and gasification, with/without catalyst; various solid wastes treatable	Excellent; different gasifying agents can be added at different heights of the riser	Very limited; restricted range of size and energy content of waste; pretreatment steps usually adopted	Limited; solid residency time and temperature profile can be varied within narrow range	Excellent
Catalytic process	Can be used for very slow, non-deactivating catalyst	Can be used for very slow, non-deactivating catalyst	Excellent temperature control, allowing large-scale operations	Heavy attrition of catalyst	Not used	Not used	Not used

Parameters	**Downdraft Fixed Bed**	**Updraft Fixed Bed**	**Bubbling Fluidised Bed**	**Circulating Fluidised Bed**	**Rotatory Kiln**	**Moving Grate**	**Plasma**
Non-catalytic process	High temperature gasifiers provide reliable, continuous operations	High temperature gasifiers provide reliable, continuous operations	Excellent for continuous operations; yields uniform product	Excellent for continuous operations	Widely used; suitable for solids, which may sinter or agglomerate	Widely used	Offers high potential for use with industrial and hazardous wastes
Scale up	Can be scaled, provided due care in temperature control	Can be scaled, provided due care in temperature control	Requires careful consideration; a pilot plant is often necessary	Some large projects are planned	Generally not relevant; various-sized kilns have been installed	Problematic due to physical length of equipment and experience requirements	Technology is offered at small scale using identical modules, therefore involves no risks in scaling-up
Cost	Major advantages are reactor simplicity and relatively low investment costs	Major advantages are reactor simplicity and relatively low investment costs.	Moderate; possibility of small-scale plants increases investment options; low maintenance costs	Higher capital costs than for BFB; generally appropriate for large-scale plants	Moderate investment cost; high maintenance costs due to moving parts, and fouling and erosion of inner walls	High investment cost; generally appropriate for large-scale plants; high maintenance costs due to moving parts	Very high investment, maintenance and operating costs; high electricity consumption

Annexure 5: Proposed standards for Segregated Combustible Fractions (SCF) and Refuse Derived Fuel (RDF)[77]

Sl. No.	Parameter	SCF	RDF - Grade III	RDF - Grade II	RDF - Grade I
1	Intended Use	Input material for Waste to Energy plant or RDF pre-processing facility	For co-processing directly or post-processing with other waste materials in cement kiln	For direct co-processing in cement kiln	For direct co-processing in cement kiln
2	Size	Material >400 mm must be mutually agreed on between ULBs and cement plant	<50 mm or < 20 mm depending upon use in ILC or SLC, respectively		
3	Ash – maximum permissible	<20%	<15%	<10%	<10%
4	Moisture – maximum permissible	<35%	<20%	<15%	<10%
5	Chlorine – maximum permissible	<1%	<1.0%	<0.7	<0.5
6	Sulphur – maximum permissible	<1.5%	<1.5%		
7	* Net Calorific Value (NCV) – in kcal/kg (Average figure of each individual consignment)	>1,500 kcal/kg net	>3,000 kcal/kg net	>3,750 kcal/kg net	>4,500 kcal/kg net
8	Parameters - other	Any offensive odour to be controlled	Any offensive odour to be controlled	Any offensive odour to be controlled	Any offensive odour to be controlled

(*Grade III RDF: MSW processed to a particle size such that 95% by weight passes through a 50 mm square mesh screen and from which most of the glass, metals and other organics have been removed; Grade II RDF: MSW processed to a course particle size with or without ferrous metal separation; Grade I RDF: MSW used as RDF in as discarded form)

[77] Source: http://164.100.228.143:8080/sbm/content/writereaddata/Guidelines%20on%20RDF%20Usage.pdf. Retrieved September 16, 2019

5. Bibliography

Ali Engineering Works. (2019, November). *Ali Engineering Works*. Available at: https://www.indiamart.com/proddetail/waste-plastic-washing-plant-6394538797.html. Retrieved May 5, 2021

All Power Labs. (n.d.). *How Gasification Works.* Available at: http://www.allpowerlabs.com/gasification-explained. Retrieved November 10, 2019

Ankur Scientific. (2019, January 17). *What is the Cost of Waste to Energy Projects in India?*. Available at: https://ankurscientific.com/blog/2018/11/25/what-is-the-cost-of-waste-to-energy-projects-in-india/#:~:text=The%20cost%20of%20installing%20a,kWh%20(coal%20to%20solar. Retrieved May 3, 2021

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. Waste Management, 32, 625-639. *Waste Management, 32*, 625-639. doi:10.1016/j.wasman.2011.09.025.

Bernard, D., Lemarchand, D., Tétreault, N., Thévenet, C., & Souancé, A. d. (2017). *Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice.* Washington, D. C.: International Finance Corporation.

Central Pollution Control Board. (2004, December). Dioxin (PCDDs) and Furan (PCDFs) - Critical Persistent Organic Pollutants (POPs). *Parivesh Newsletter*, p. 24.

Central Pollution Control Board. (2015). *Assessment & Quantification of Plastics Waste Generation in Major Cities.* New Delhi: Ministry of Environment, Forest and Climate Change, Govt. of India.

Central Pollution Control Board. (2017). *Guidelines for Co-processing of Plastic Waste in Cement Kilns.* New Delhi: Ministry of Environment, Forest and Climate Change.

Central Pollution Control Board. (2019). *Annual Report for the year 2018-19 on Implementation of Plastic Waste Management Rules.* New Delhi: Ministry of Environment, Forest and Climate Change, Govt. of India.

Central Public Health and Environmental Engineering Organisation. (2016). *Manual on Municipal Solid Waste Management.* New Delhi: Ministry of Urban Development, Govt. of India.

Centre for Innovations In Public Systems. (2014). *Use of Plastics in Road Construction Implementation of Technology and Roll out.* Hyderabad: Centre for Innovations In Public Systems.

Chang, S.-T., Chou, M.-S., & Chang, H.-Y. (2014). Elimination of Odors Emitted from Hot-Melting of Recycle PS by OxidativeReductive Scrubbing. *Aerosol and Air Quality Research, 14*, 293-300. doi: 10.4209/aaqr.2013.01.0014.

CN cemnet. (2020, July 27). *Japanese cement producers help reduce plastic waste.* Available at: https://www.cemnet.com/News/story/169254/japanese-cement-producers-help-reduce-plastic-waste.html. Retrieved April 5, 2021

Dr. Sambale, -I. H. (2005, June 20). *PET Recycling without Caustic Soda*. Available at: https://en.kunststoffe.de/a/news/pet-recycling-without-caustic-soda-268962. Retrieved November 20, 2019

Dr. Vyas, D. S., Mr. Dave, U. B., & Ms. Parekh, H. B. (2011). Plasma Pyrolysis : An Innovative Treatment to Solid Waste of Plastic Material. V.V.Nagar: National Conference on Recent Trends in Engineering & Technology.

du Pont de Nemours and Company. (2011). *Proper Use of Local Exhaust ventilation During Processing of Plastics .* du Pont de Nemours and Company.

Dutta, A., & Acharya, B. (2011). Production of bio-syngas and biohydrogen via gasification. In R. Luque, J. Campelo, & J. (. Clark, *Handbook of Biofuels Production: Processes and Technologies* (pp. 420-459). Woodhead Publishing Limited.

Dutta, S. (2017, September 4). *Recycling Plastic In India: Converting Plastic Waste To Fuel, The Unrealised Potential.* Available at: https://swachhindia.ndtv.com/recycling-plastic-in-india-converting-plastic-waste-to-fuel-the-unrealised-potential-9436/. Retrieved December 12, 2020

Dwivedi, A., Mattoo, M., Prabhu, J., Dwivedi, A., & Jain, P. (2017). A Survey on Cost Comparison of Sustainable Plastic Road with Regular Bitumen Road. *International Journal of Innovative Research in Science, Engineering and Technology, 6(2)*, 1500-1506. doi:10.15680/IJIRSET.2017.0602011.

Entrepreneur India TV. (2019, February 20). *LDPE Plastic Recycling Business | How To Start LDPE Plastic Recycling Business [Video].* Available at: https://www.youtube.com/watch?v=37W6FZKJmm8. Retrieved March, 2021

Expert Committee Constituted by MOHUA. (2018). *Guidelines on Usage of Refuse Derived Fuel in Various Industries.* New Delhi: Ministry of Housing and Urban Affairs.

Farag, H., Gidlund, M., Sisinni, E., & Österberg, P. (2019). Priority-Aware Wireless Fieldbus Protocol for Mixed-Criticality Industrial Wireless Sensor Networks. *IEEE Sensors Journal, 19(7)*, 2767-2780. doi: 10.1109/JSEN.2018.2888729.

Gamaralalage, P. J., & Onogawa, K. (2019). *Strategies to Reduce Marine Plastic Pollution from Land-based Sources in Low and Middle - Income Countries.* Osaka, Japan: United Nations Environment Programme, IGES Centre Collaborating with UNEP on Environmental Technologies.

Gershman, Brickner and Bratton Inc. (2013). Gasification of Non-Recycled Plastics From Municipal Solid Waste In the United States. VA: The American Chemistry Council.

Grigore, M. (2017). Methods of Recycling, Properties and Applications of Recycled Thermoplastic Polymers. *Recycling 2017 2(4), 24*, doi: https://doi.org/10.3390/recycling2040024.

Hammon, D. (2020, February 5). *IKEA Commits to Biodegradable Mushroom Packaging*. Available at: https://news.yahoo.com/ikea-commits-biodegradable-mushroom-packaging-220023480.html?guccounter=1. Retrieved December 20, 2020

Health & Safety Authority. (2014). *Local exhaust ventilation Guidance.* Dublin: Health & Safety Authority.

Hemanth. (2019, April 19). Manager, Godrej Consumer Products Limited. (H. Kolli, Interviewer)

Indian Road Congress. (2013). Guidelines for the Use of Waste Plastic in Hot Bituminous Mixes (Dry process) in Wearing Courses. New Delhi, India: Indian Roads Congress.

Industrial Extrusion Machinery. (n.d.). *Types of Plastic Extruders.* Available at: http://www.industrialextrusionmachinery.com/types_of_plastic_extruders.html. Retrieved January 24, 2020

Jain et al., J. (2018). Accelerating India's Circular Economy Shift A Half-Trillion USD Opportunity Future-proofing growth in a resource-scarce world. New Delhi: FICCI and Accenture.

Jefferson, H., Dvorak, R., & Kosior, E. (2009). Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526)*, 2115–2126. doi: 10.1098/rstb.2008.0311.

Jiménez, L., Mena, M. J., Prendiz, J., Salas, L., & Vega-Baudrit, J. (2019). Polylactic Acid (PLA) As A Bioplastic And Its Possible Applications In The Food Industry. *HSOA Journal of Food Science and Nutrition, 5 (2)*, doi:10.24966/FSN-1076/100048.

Kalargaris, I., Tian, G., & Gu, S. (2017). Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil. *Fuel Processing Technology, 157*, 108-115. doi:https://doi.org/10.1016/j.fuproc.2016.11.016.

Kumar, P. U. (2016). Cost estimation and procedure to set up 1 MW waste-to-energy gasification plant in India. Halmstad University.

Lord, R. (2016). Plastics and Sustainability:A Valuation of Environmental Benefits, Costs and Opportunities for Continuous Improvement. Trucost.

M/s Vishwakarma Machine Tools. (n.d.). *M/s Vishwakarma Machine Tools*. Available at: https://www.indiamart.com/proddetail/plastic-waste-grinder-15025996091.html. Retrieved May 5, 2021

Maschinen- und Anlagenbau Schulz GmbH. (2019, November). *Your benefit with a dry cleaning system DRD*. Available at: https://www.mas-austria.com/en/your-benefit-with-mas/a-dry-cleaning-system-drd. Retrieved May 3, 2021

Md. Hossain, S., Md. Hosen, D., Hossen, S., Md. Islam, A., & Md. Khan, H. K. (2020). Tensile Strength of Paper Produced from Different Body Parts of Water Hyacinth. *International Journal of Current Engineering and Technology, 10(2)*, 214-217. doi:10.14741/ijcet/v.10.2.4.

Ministry of Environment, Forest and Climate Change. (2016, April 8). *Solid Waste Management Rules*. New Delhi, India: Ministry of Environment, Forest and Climate Change.

Ministry of Housing & Urban Affairs, Govt. of India. (2019). *Plastic Waste Management: Issues, Solutions & Case Studies.* New Delhi: Ministry of Housing & Urban Affairs, Govt. of India.

Mr.Sabharwal, S. M. (2019, July). Executive Director. (R. Thakur, R. Singh, and A. R. Sekhar, Interviewers)

Municipal Administration Department, Government of Telangana. (2020, July 14). Circular on collection of non- recyclable singte use ptastics & Setting up plants to convert waste ptastics to fuet oit - proposat submitted by M/s.Pyrogreen, Energy Pvt.Ltd., Hyderabad-Consider the proposal and Handover collected non-recyclable ptastic with the agency if not tied up with any other agencies - Reg.Hyderabad: Government of Telangana

Paprec Group. (n.d.). *Sorting Plastic Waste.* Available at: https://www.paprec.net/en/understanding-recycling/recycling-plastic/sorting-plastic-waste. Retrieved November 11, 2019

Plastic Waste Management Institute. (2019). *An Introduction to Plastic Recycling* . Tokyo: Plastic Waste Management Institute.

Sampath, M. (2019, November 17). Managing Director. (A. Adhikari, Interviewer)

Sexton, C. (2019, March 15). *Plastic pollution becoming one of the world's biggest health threats*. Available at: https://www.earth.com/news/plastic-pollution-health-threats/. Retrieved October 11, 2019

Sharuddin, S. D. A.; Abnisa, Faisal; Daud, W. M. A. W.; Aroua, M. K. . (2016). A review on pyrolysis of plastic waste. Energy Conversion and Management. *Energy Conversion and Management, 115*, 308-326.

Stephen, A. A., & Prof. Paranjpe, A. (2015). Plastic Waste of Jabalpur City used for Energy Recovery. *International Journal of Recent Development in Engineering and Technology, 4(9)*, 40-44.

TAAPMA (2019, November). (H. Kolli, Interviewer)

The Hindu. (2017, November 11). *Plastic bottles turn mattresses, quilts & much more*. Available at: https://www.thehindu.com/sci-tech/energy-and-environment/plastic-bottles-turn-mattresses-quilts-much-more/article18714374.ece. Retrieved November 10, 2019

The Institute for Industrial Productivity. (n.d.). *Use of Waste Plastics as Fuel.* Available at: http://www.iipinetwork.org/wp-content/Ietd/content/use-waste-plastics-fuel.html. Retrieved April 5, 2021

The Japan Containers and Packaging Recycling Association. (n.d.). Available at: https://www.jcpra.or.jp/english/tabid/612/index.php. Retrieved April 5, 2021

The Japan Containers and Packaging Recycling Association. (2020). *The Containers and Packaging Recycling System in Japan.* Tokyo: The Japan Containers and Packaging Recycling Association.

The Teijin Group. (2005). *CSR Report.* Tokyo: The Teijin Group.

Tsakona, M., & Rucevska, I. (2020). *Plastic Waste Background Report (Draft).* Beau Vallon, Seychelles: Secretariat of the Basel Convention.

TSPCB (2019, November). (S. Shroff, Interviewer)

United Nations Environment Programme. (2009). *Converting Waste Plastics into A Resource: Compendium of Technologies.* Osaka: United Nations Environment Programme.

United Nations Environment Programme, Caribbean Environment Programme. (2019). *The Plastic Pollution Pandemic*. Available at: https://www.unenvironment.org/cep/news/blogpost/plastic-pollution-pandemic. Retrieved December 5, 2019

United Nations Industrial Development Organizations. (n.d.). *Biofuel and Waste Management: C-POWER Plant.* Available at: http://www.unido.or.jp/en/technology_db/1643/. Retrieved May 3, 2021

University of Leeds, UK. (2014). *Web Presentation Learning Resource.* Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5aedb2351&appId=PPGMS. Retrieved May 3, 2021