P2G Safety Toolkit

Risk Management & Safety Controls in Plastic Upcycling

2025 WINNER Cambridge Research Impact & Engagement Award

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Contents

The main objective of this document is to establish comprehensive guidelines ensuring the overall safety of a plastic waste recycling facility designed specifically for Nepal.
Furthermore, it aims to help in selecting safe and reliable safety equipment.

About This Toolkit & Overview

This toolkit provides comprehensive guidelines for the safe design and operation of plastic recycling facilities, aiming to achieve both worker protection and enhanced productivity.

What this manual aims to achieve

Plastic reprocessing machines can make the workforce in the plastic waste recycling industry susceptible to various hazards. For example, the melting process is crucial for mechanical plastic recycling as it allows the polymers to be soft and elastic enough to be formed into various applications. However significant discomforts such as harmful fumes can arise. Safeguarding the well-being of personnel and ensuring the safe operation of equipment are most important in the pursuit of sustainable and responsible plastic recycling practices.

This document reviews the process and the safety hot spots, to share the hands-on know-hows captured from the project P2G in support of FabLab Nepal between 2022 to 2026.

How we designed this toolkit

The integration of Occupational Health and Safety (OHS) measures contributes significantly to the overall performance of a company (Jallon et al., 2011). The consideration and efficient implementation of safety allows the reduction of risks associated with accidents; consequently reducing costs to the employer. In addition it can create a strong business competitiveness when the safety indicator is a decisive factor in the choice of suppliers (Borges Soares et al., 2021).

Safety is indispensable across various plastic processing industries, including plastic recycling. Prioritising workplace safety not only protects workers, equipment, and the environment but also ensures regulatory compliance. The proactive approach can prevent injuries, lawsuits, and concurrently improve the overall efficiency and productivity of the facility. Overall safety should be considered while setting up a plastic recycling facility which consists of different types of safety as presented in Figure 1 below:

CORE PROCESS	FACILITY PLANNING	SAFETY SYSTEMS	RISK CONTROL
1. Safety in Preprocessing	3. Selecting Safe Locations	5. Maintenaning Equipment & Machine	8. Preventing Fire
		6. Handling Material	9. Environmental Safeguards
2. Managing Risks in Plastic Forming	4. Designing Facility Layout	7. Protecting Workforce	10. Gas and Fume Management

Figure 1 *Overall Safety Components*

The Growing Challenge of Plastic Waste

The convenience of plastic has created an inconvenient truth. Earth is drowning in plastic waste. Yet within this crisis lies an opportunity for transformation through effective recycling.

Introduction to Plastic Recycling

Plastics are widely used due to their economic viability and ease of production. However, the prevailing pattern of plastic consumption and disposal is increasingly unsustainable. Conventional disposal methods, such as landfilling and incineration, not only pose environmental hazards but also contribute to the exacerbation of global warming (Markandeya et al., 2022). As of 2023, the annual plastic production volume reached approximately 380 million metric tons (Statistica, 2023).

The plastic waste presents both challenges and opportunities that demand the exploration of best solutions (Markandeya et al., 2022). Plastic recycling stands out as a crucial step in environmental conservation, not only mitigating the adverse impact on the environment but also fostering employment opportunities and curbing the emission of greenhouse gasses. The New Jersey WasteWise Business Network has delved into the economic advantages of recycling, highlighting the financial savings achievable through effective waste recycling initiatives (Wise, 2013).

Plastic recycling is the process of converting waste plastic into new materials and objects. This sustainable practice serves as an alternative to traditional waste disposal methods, preserving the embedded value of polymers and contributing to the reduction of greenhouse gas emissions. Among various plastic recycling methods, mechanical recycling stands out as the most widely used technology for the large-scale treatment of solid plastic waste. This method encompasses a series of steps, including washing, shredding, melting, and remoulding of the polymer (Garcia & Robertson, 2017). The mechanical recycling of plastics consists of the following stages.

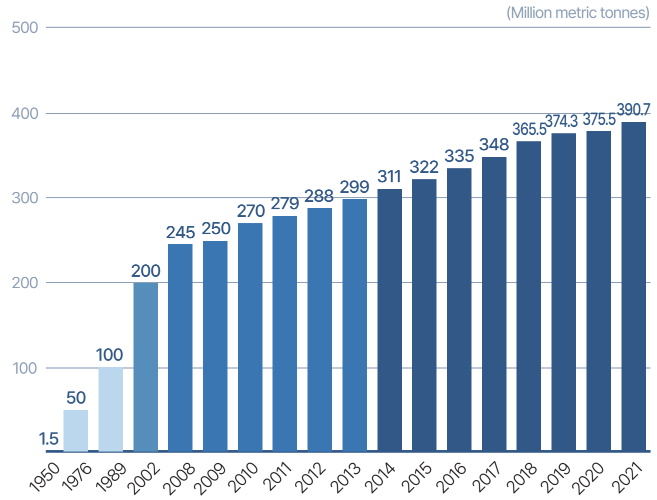


Figure 2 *Annual production of plastics worldwide from 1950 to 2021* (Source: Statista)

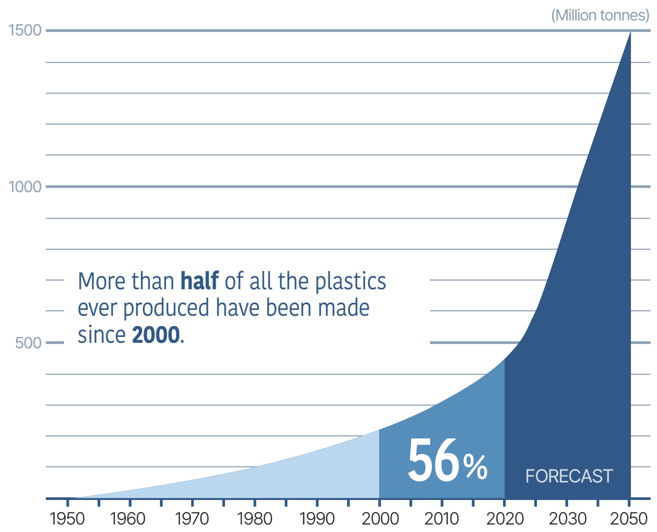


Figure 3 *Global annual plastic production* (Source: Plastic Source Foundation)

Plastic recycling transforms plastic waste into valuable resources through a series of processes including washing, shredding, melting, and remoulding.
This sustainable practice not only preserves the embedded value of polymers but also creates economic opportunities whilst reducing environmental impact.

1. Safety in Preprocessing

The first 5 stages describe the preprocessing of the plastic waste as the raw materials.

a. Collection

The initial stage involves the collection of plastic waste from residences and commercial establishments. Plastic waste is sourced through government recycling programs, private collection companies, informal pickers, drop-off centers, and designated events. A critical aspect of this process is the separation of plastic from other recyclables, such as paper and metal.

b. Inspection/Sorting

Following collection, the plastic waste undergoes a meticulous sorting process based on plastic type and colour. This stage is crucial due to the distinct properties of various types of plastic and effective recycling of mixed plastics is normally difficult. For instance, polyethylene terephthalate (PET) bottles are recyclable into new PET bottles, but they are not compatible with the recycling process for polyethylene (PE) bags. Accurate sorting ensures that each type of plastic is directed to the appropriate recycling stream, enhancing the efficiency and quality of the recycling process.

c. Washing/Cleaning

This stage is for removing dirt, food residue and other contaminants from the plastic waste. The cleaning process is vital to guarantee that the recycled plastic attains a high standard of cleanliness, ensuring its safety for subsequent use.

Table 1 *Hazards and required PPEs in the plastic waste collection stage*

Hazards
Waste collection workers can be exposed to unexpected sharp or contaminated objects (viruses, fungi, toxic gases) hidden in the waste.
Required PPEs
· Safety gloves · Face masks · Aprons · Safety Shoes · Goggles

Table 2 *Hazards and required PPEs in the plastic waste inspection/sorting stage*

Hazards
· Waste collection workers can be exposed to unexpected sharp or contaminated objects (viruses, fungi, toxic gases) hidden in waste. · Physical and mental well-being of repetitive work.
Required PPEs
· Safety gloves · Face masks · Aprons · Safety Shoes · Goggles

Table 3 *Hazards and required PPEs in the plastic waste washing/cleaning stage*

Hazards
Sewage and wastewater.
Required PPEs
· Safety gloves · Face masks · Aprons

d. Drying

After washing, the plastic waste undergoes a drying process to eliminate moisture, residual food, and other contaminants. Drying is to prepare the plastic for subsequent operations (community.preciousplastic.com, 2022). Ensuring that the plastic is thoroughly dried enhances the production quality of recycled materials.

e. Chopping/Shredding/Grinding

In this stage, the dried plastic undergoes the mechanical actions to break down the plastic into smaller, manageable pieces using shredder or grinder. The reduction in size enhances the efficiency of the melting process.

This preparatory step is for achieving a consistent and uniform feedstock for the recycling process.

Figure 4 *Plastic shredding machine* ©Universidad Pontificia Comillas

f. Melting and Pelletising optional

The plastic flakes generated from the shredding process undergo a melting and pelletising process. In this stage, the flakes are melted to form a liquid state. Subsequently, the molten plastic is shaped into pellets, which are then cooled and solidified. This transformation from a liquid to solid form is a key step in the recycling process, creating uniform pellets that can be utilised as raw material for the manufacturing of various plastic products. In a small-scale production, shredded plastic is used directly from process e(chopping/shredding/grinding). However, uniform pellets can ensure controlled quality of the end product in large-scale manufacturing.

Table 4 *Hazards and required PPEs in the plastic waste drying stage*

Hazards
Carrying and loading wet plastics in a drying system needs excessive forces resulting in awkward body postures.
Required PPEs
· Safety gloves · Aprons · Implementing ergonomic safety procedures for carrying and loading plastics.

Table 5 *Hazards and required PPEs in the plastic waste chopping/shredding/grinding stage*

Hazards
· Feeding the hopper can cause a hand injury. · The small particles can cause eye injury.
Required PPEs
· Safety gloves · Face masks · Aprons · Safety Shoes · Goggles

Table 6 *Hazards and required PPEs in the plastic waste melting/pelletising stage*

Hazards
· Hot temperatures can create burns · Fume generation during melting
Required PPEs
· Leather gloves · Face masks · Face Shields · Aprons · Safety Shoes · Goggles

2.
Managing Risks in Plastic Forming

From this stage, the preprocessed plastic waste is utilised as the raw material for **transforming** into end-products for various applications. This stage involves thermal processing/melting with a varying level of heat depending on the melting temperatures of different polymer types.

a. Extrusion

The plastic is melted and extruded through a die to produce new pellets or other desired shapes. The die can be customised to create various plastic products, including bottles, bags, or containers. During this process, it should be noted that fumes may emit from different points as below.

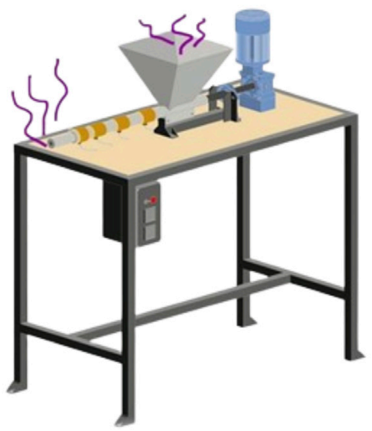
i. From the Nozzle

Fumes may be released from the nozzle, especially when the extrusion process is in operation

ii. Hopper and Mould Openings

Some fumes may emerge from the hopper, particularly if it is not obstructed by pellets. Additionally, fumes may be observed from the mould openings during specific production processes.
For instance, when creating a beam, fumes may be noticeable at the end of the beam mould. It is important to manage and monitor these fumes to ensure a safe and environmentally conscious extrusion process.

Figure 5
Extruder
©Precious Plastic



b. The Polyfloss Machine

The Polyfloss machine is designed to process molten plastics into a fibrous format similar to cotton wool. It should be operated with the considerations of the following parts for fume emissions.

i. From the Outlet

The primary source of fumes is the outlet of the Polyfloss machine. Most emissions occur from this point during the operation.

ii. Hopper and Pellets

Fumes may also be observed emanating from the hopper if it is not obstructed by pellets. Proper management of the hopper is essential to control the fume release. Closing the lid after feeding pellets is recommended to prevent dispersion of fumes. Also, proper ventilation gives a safer environment to work in.

Figure 6
Polyfloss Machine
©Emile De Visscher

c. The Sheet Press

The Sheet Press is specifically designed for crafting flat-shaped plastic tiles and boards. The shredded plastic or pellets are placed in the press mould, then a certain level of heat and pressure are applied to evenly distribute the polymer and form a flat-surfaced product. Here are considerations regarding fume emissions during its operation:

i. Heating plate

The primary emission source is observed from all four sides of the heating plate of the Press during the operation.

ii. Uneven Heating

If heating is uneven, fumes may be noticeable from certain overheated areas. Ensuring uniform heating reduces excessive fume emissions from accidental overheating.

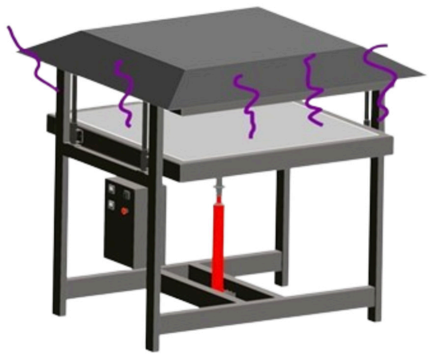


Figure 7
Sheet Press Machine
©Precious Plastic

d. Injection Moulding

Injection moulding process includes melting of plastic into hot and soft form so as to cast them into an open cavity or die. The casted plastics are solidified into a plastic product. Fume emissions can occur from the plastic pellets container as shown in Figure 8.

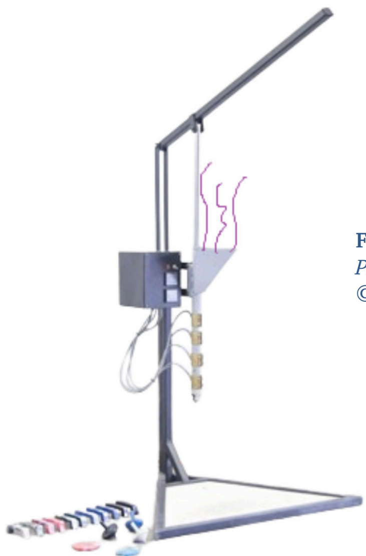


Figure 8
Plastic Injection Machine
©Precious Plastic

3.
Selecting Safe Locations

Selecting an appropriate location for a plastic recycling facility ensures the safety of both workers and the surrounding environment.

Establishing and adhering to a set of location safety standards mitigate potential hazards associated with the recycling process. In addition, it is economically important to consider factors such as the raw material source, market location and availability of workforce when selecting the location of the recycling facility (Kiran, 2022). For ensuring a safe location, following factors should be considered:

a. Community Area:
The chosen location should maintain a sufficient distance from residential areas to prevent any direct impact on the health of the local community. This precautionary measure is essential in ensuring the well-being of residents and minimising potential health risks associated with the operations of the facility.

b. Accessibility for Emergency Services:
Proximity to emergency services, such as hospitals and fire control centres is essential. Ensuring these services nearby enhances the facility's capability to respond promptly and effectively to unforeseen incidents, thereby safeguarding the well-being of workers and addressing any potential emergencies that may arise during the plastic recycling process.

c. Transportation Access:
A secure access to transportation is essential to guarantee the safety of both materials and the workforce during transportation. Implementing safe and reliable transportation methods and the access to the facility minimises the risk of accidents and ensures the well-being of all involved in the logistics of material movement within the plastic recycling facility.

Once a suitable location is identified, it is imperative to address and mitigate potential adverse effects on the environment through an **Environmental Impact Assessment (EIA)** in accordance with the Industrial Enterprise Act (The Industrial Enterprises Act, 2020).

Figure 9
Plastic Hub in Ree Village
©Impact Hub Kathmandu

4.
Designing Facility Layout

A poorly planned layout can elevate the risks of accidents and injuries, impede emergency response efforts, and diminish operational efficiency. Designing an effective facility layout ensures a streamlined production process and enhances overall economic efficiency.

a. Machine Arrangements:
The arrangement of machines within the facility primarily focuses on prioritising worker safety, operational efficiency, and accessibility. The overall safety of the process facility relies on maintaining sufficient separation between machines (de Lira-Flores et al., 2019). Machines should be strategically placed to ensure ample aisle space, facilitate safe material handling, and provide easy access for maintenance and repair activities. This careful arrangement not only minimises the risk of accidents but also optimises the functionality of the facility.

b. Hot Material Handling Time:
The facility layout should be designed to enable the safe and efficient handling of hot materials, aiming to minimise the exposure time for workers to potential hazards. This involves establishment of designated workstations equipped with necessary safety measures, adherence to safe handling protocols, and the provision of accessible wash basins for immediate response to any potential contact with hot materials. Ensuring a layout that prioritises safety in handling hot materials contributes to a secure working environment for the workforce.

c. Adequate Illumination:
An essential aspect of the facility layout is to ensure sufficient illumination throughout the facility, encompassing workstations, storage areas, and emergency exits. This involves incorporation of task lighting, utilisation of natural light, and the integration of backup lighting systems. In confined spaces where natural lighting may be insufficient, temporary lighting solutions become essential (Moatari Kazerouni et al., 2012). Adhering to the Nepal National Building Code, 2015, guidelines regarding minimum open areas for natural lighting and ventilation is recommended (NBC 206: 2015). Additionally, the government's recommendations on minimum light illumination levels for workplaces based on the type of work and location should be followed: lux (unit of illumination) levels should not fall below the prescribed range of 10 to 100 (National Occupational Safety and Health Profile for Nepal, 2022).

d. Electric Outlets:
A well-planned layout should incorporate an ample number of electric outlets positioned strategically to power machinery, equipment and lighting systems. Since plastics are flammable, having a short circuit in a facility can bring huge loss. Prevention of short circuits should be done by proper arrangement of outlets to ensure adequate, efficient and safe power distribution. Additionally, the layout should encompass provisions of emergency power sources and reliable backup systems to mitigate potential disruptions in case of power outages.

e. Emergency Evacuation Route:
The facility layout must incorporate clearly designated emergency evacuation routes that are well-lit, unobstructed, and easily accessible. This encompasses the provision of clearly marked fire exits, designated assembly areas, and detailed evacuation procedures.

Implementing a Systematic Layout Planning, an approach to factory layout planning developed by Richard Muther (1973), is pivotal for the layout design and planning of any industry. Gozali et al. utilised this approach to design a plastic bag factory layout in Indonesia (Gozali et al., 2015).

5. Maintaining Equipment & Machine

Ensuring machine safety is equally important to maintaining the functionality of the industry under all conditions. This involves the implementation of regular maintenance procedures and proper guarding of moving parts.

a. Risk Assessments:
A comprehensive assessment of the risks associated with each machine employed in the facility, including potential hazards, control measures, and risk level should be done. Special attention must be given to machines with substantial force or heat that could cause injuries during start-up or operation (Machinery and Equipment Safety, 2007).

b. Emergency Stop Systems:
Ensuring machine safety involves the installation of emergency stop systems on each machine. This includes defining their precise location, functionality, and implementing regular testing protocols. Easily accessible emergency stop buttons or pull cords should be strategically placed near each machine, accompanied by routine testing procedures to guarantee their effectiveness in times of need.

c. Safe Operating Procedures:
A document of the safe operating procedures for each machine should be included covering start-up, operation, shut-down, and maintenance procedures, as well as information on supervision and communication protocols (Moatari Kazerouni et al., 2012). There should be a checklist of important steps for safe operation of each machine.

d. Maintenance Plan:
A plan for the regular maintenance of each machine should be developed including schedules, responsibilities, and documentation requirements, as well as information on spare parts, repair procedures, and safety protocols during maintenance. A well-structured maintenance plan contributes to the longevity and safe operation of machines.

e. Warning Signs and Labels:
A description of the warning signs and labels used on each machine should be provided including their location, content, and compliance with relevant standards, as well as procedures for maintaining the signs and labels. The signs indicating potential hazards such as **high temperature, do not enter without masks** should be created. All warning signs and labels must be visible and easily understandable.

f. Machine Guards:
Installation of machine guards on each machine is a fundamental aspect of machine safety. This involves defining the design, construction, and ensuring compliance with relevant safety standards. Machine guards play a crucial role in preventing access to hazardous areas, safeguarding workers from potential injuries.

g. Machine Isolation:
Clearly defined procedures for isolating machines during normal operations, maintenance, or repair, should be established. Specific consideration should be given to each machine
e.g. Polyfloss Machine disperses plastic fibres within the facility space, in outlining isolation protocols to ensure the safety of personnel and equipment during the operations.

Figure 10
Machines in FabLab Nepal
©FabLab Nepal

6. Handling Material

Raw materials are converted into final products using the machining process. Raw materials for plastic recycling range from the waste in their original shapes to the pellets processed from recycled plastics. Collection and sortation are required for the raw waste before going to the shredding process.

a. Safe Storage:
Procedures should be established for the safe storage of the raw materials, including storage areas, container specifications, labelling requirements and inventory controls to prevent contamination, degradation or accidents. These ensure the integrity of raw materials throughout the recycling process.

b. Material Supply:
Maintaining the purity of materials is important in plastic recycling. Avoiding mixing of different types of plastics preserves recyclability. Implementing a pure supply of materials helps prevent the introduction of contaminants or adulterants. Additionally, Mechanising material-feeding processes reduces the risk of hazardous situations compared to manual feeding (United States Department of labour, 2020).

c. Working Conditions:
The working conditions for handling materials should be safe and well-maintained, including temperature and humidity controls to prevent accidents, injuries or exposure to harmful conditions. A well-maintained working environment contributes to prevention of voids and irregularities in recycled products.

d. Material Handling Equipment:
Appropriate material handling equipment such as heat resistant gloves, steel toe boots should be provided and maintained to facilitate safe and efficient handling of materials. This helps prevent injuries and ensures the quality of the final product. Well-maintained equipment contributes to enhancing overall operational safety.

7.
Protecting Workforce

Workforce safety is fundamental to human resource management, encompassing measures that prevent workplace accidents, injuries, and illnesses while promoting employee well-being and productivity. And life of each equipment should be accessed and analysed along with proper guidelines for replacement of each type of personal protective equipment.

a. Safety Training and Education:

Safety Training and Education should be tailored to the specific risks and tasks associated with each worker's job. In addition, hands-on training should be provided periodically to ensure that workers maintain their knowledge and familiarity. The training includes a review of safety procedures, emergency response, equipment operation and hazard identification and control.

b. Hazard Communication Protocols:

Hazard communication protocols should be established to ensure that workers are aware of potential hazards, and know how to protect themselves. Also, establishing a system for reporting accidents/incidents encourages open communication about their safety concerns. Investigating these occurrences helps identify the root causes and implement corrective actions.

c. Noise, Smoke, and Dust Control:

Integrating measures for controlling noise, smoke, and dust is especially vital for workforce safety in the recycling facility. This involves installation of acoustic barriers, ventilation systems and dust collection systems. Compliance with recommended noise levels, such as below 85 dB for an eight-hour workday (Brauer, 2006), contributes to a healthier and safer work environment.

d. Personal Protective Equipment (PPE):

Personal protective equipment are devices or materials created to protect the wearer or users from potential injury or contamination. This includes protective clothing, safety glasses, helmets, hearing protection, and respiratory protection. It ensures protection against health and safety risks not just for workers but also for the people in the surrounding environment. Scientific selection of PPEs can be found in the toolkit for safety and health for engineers by Brauer (2006). There are seven basic type of PPE according to Anbusafety (Personal Protective Equipment List with Pictures and Function, 2024):

i. Respiratory protection:

Respiratory protection aims to safeguard the respiratory system from inhaling harmful substances such as dust, fumes, gases, or airborne pathogens. Filtered safety masks are used for respiratory protection.

ii. Eye and face protection:

Eye and face protection is to safeguard the eyes from potential hazards like flying particles, chemical splashes or intense light. Safety glasses, goggles, and face shields are employed to protect against dust, mists, fumes, vapour, projectiles, and gases that may be harmful to the eyes or cause irritation.

iii. Head protection:

Head protection is intended to protect the head from impact, falling objects, electrical shocks, or other head-related injuries. Safety helmets and hard hats are worn to protect the head against falling objects such as wooden beams and loose bricks.

iv. Hand protection:

Hand protection is designed to shield the hands from cuts, abrasions, punctures, chemical exposures, or thermal hazards. Safety gloves are used to protect hands from contact with sharp objects.

v. Foot protection:

Foot protection aims to prevent injuries to the feet and legs from falling or rolling objects, crushing, punctures, or electrical hazards. Safety shoes are worn to prevent injuries to the feet from falling objects such as bricks.

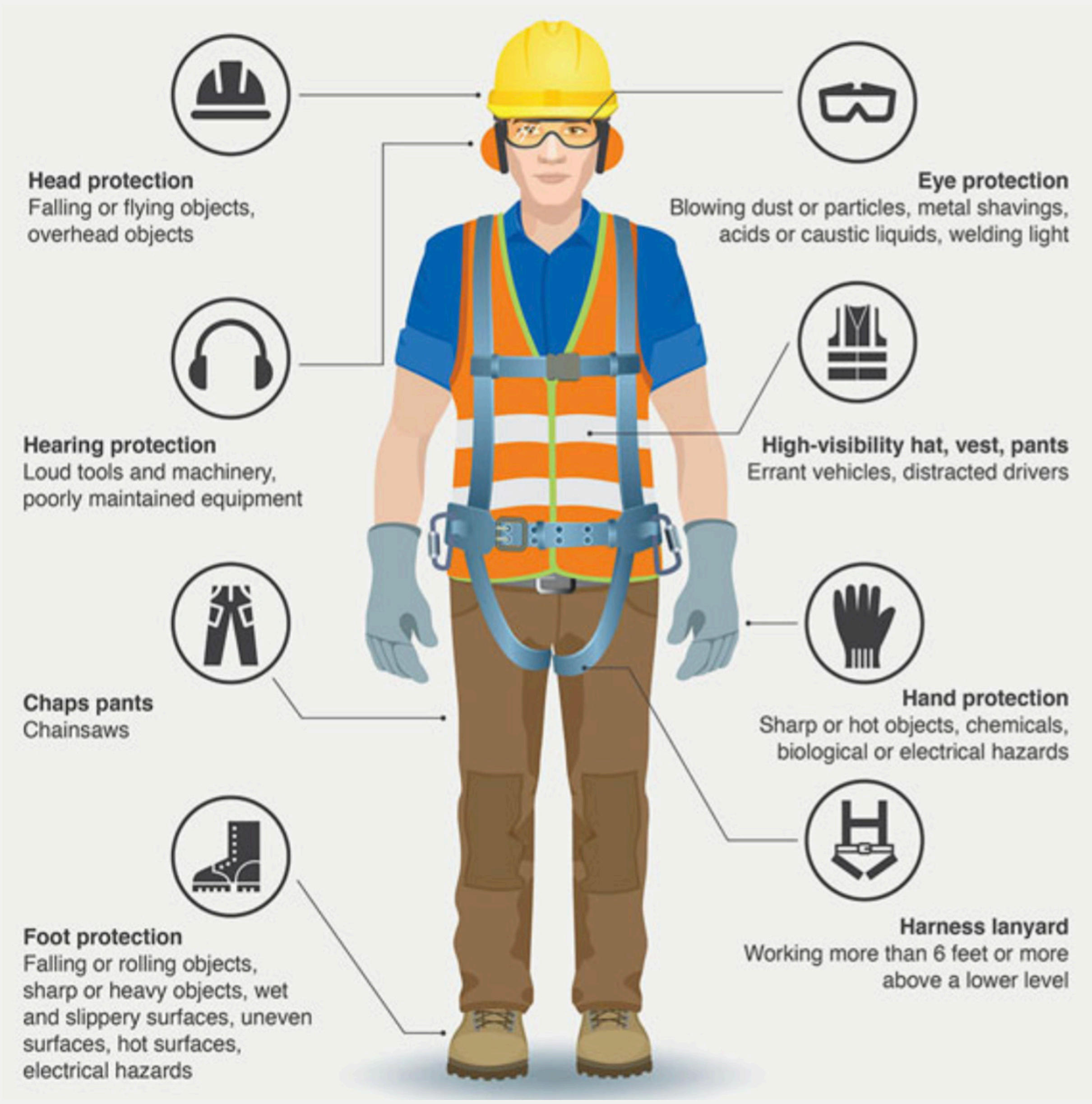


Figure 11 *Types of PPEs* ©Anbusafety

Rubber boots can be worn to protect from chemical exposure.

vi. Body protection:

Body protection covers the torso and limbs, providing protection against various hazards such as extreme temperatures, chemical exposure, or mechanical impacts. It involves wearing appropriate clothing, such as aprons, vests, full-body suits, or flame-resistant clothing to protect the entire body from the harmful effects of the working environment.

vii. Hearing protection:

Hearing protection, such as earmuffs and earplugs, is employed to cover and protect the wearer's ears from excessive noise pollution, dust, or temperature variations.

8. Preventing Fire

Plastic recycling poses unique fire safety challenges due to the combustible nature of plastics and heat processing involvement.

a. Fire Detection and Alarm System:
A fire detection and alarm system serves to detect the early signs of fire and promptly alert personnel, allowing a quick response to mitigate potential damage.

b. Fire Prevention System:
Measures must be taken to prevent fires from occurring, such as regular maintenance and inspection of electrical systems, proper storage and handling of flammable materials, and regular training.

c. Fire safety drills
Fire safety drills should be conducted regularly. Information on procedures for evacuation, fire escape routes and exits, including signage and maintenance are needed for all personnel in the event of a fire. The plan should also include procedures for training and maintaining the effectiveness of the fire response plan.

9. Environmental Safeguards

Environmental safety is essential for responsible and sustainable business practices. It encompasses measures to minimize industrial environmental impact, including proper waste management, pollution prevention, and regulatory compliance.

a. Proper Waste Management
Considering the inorganic nature of plastic recycling waste, a comprehensive approach to waste reduction and recycling processes must be implemented. Protocols should be established for safe handling, storage and disposal of hazardous waste. It is imperative to prohibit the burning of plastic waste/scrap, dumping or any other unauthorised methods (Bureau of Indian Standards, 1998). In case of landfill disposal, non-degradable plastics should be properly labelled (Plastics-Recovery and Recycling of Plastics Waste-Guidelines, 2023).

b. Pollution Prevention
Pollution such as emission, wastewater and noise must be controlled to keep the working environment as safe as possible. Proper air filtration systems, waste disposal measures and acoustic insulations must be adopted for ensuring safety of the surrounding environment.

c. Compliance with Regulatory Requirements
Compliance with the local environmental regulations related to air and water pollution, hazardous waste management, and greenhouse gas emissions must be properly practised to ensure environmental safety.

Table 7 *Thermal Breakdown of common plastics (Unwin et al., 2010)*

Polymer Type	Thermal Degradation Products	Health Effects
PVC	Benzene	May cause cancer and heritable genetic damage, toxic by contact
	Naphthalene	Probably carcinogenic to humans
	Methyl Chloride	Serious damage to health by prolonged inhalation
PP	Pentane	
	Butane	
	Propane	
LDPE	Toulene	Harmful by inhalation, Possible risk of unborn child
	Butane	
	Butene	
ABS	Styrene	Irritating to skin
	1, 3-Butadiene	Carcinogenic (IARC, 2009)
	Acrylonitrile	Probably carcinogenic to humans (IARC, 2009)
PS	Benzene	May cause cancer and heritable genetic damage, toxic by contact
	Styrene	Irritating to skin
	Acetaldehyde	Irritating to the respiratory system and skin

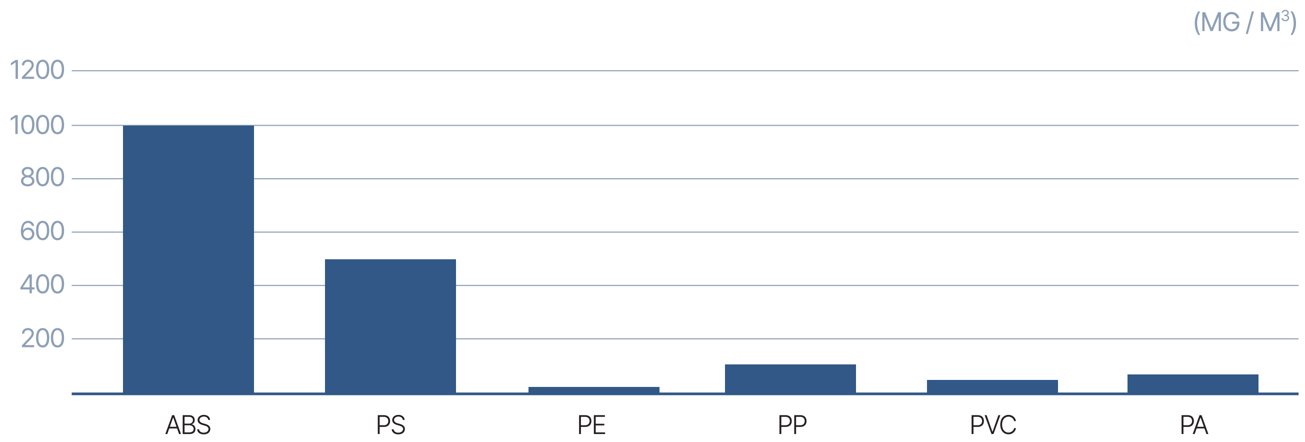


Figure 13 *Fumes contents of common plastics* (Source: University of Tokyo)

10. Gas & Fume Management

Gas safety is particularly important in plastic recycling facilities due to hazardous gases from polymer melting, including hydrocarbons, solvents, and flammable gases. It ensures safe handling and control to prevent leaks and exposure to harmful fumes.

a. Fumes generation and detection

The composition of fumes generated from heated plastic is complex. In plastic recycling, PP (Polypropylene) and PE (Polyethylene) are relatively safe to melt as they are essentially refined waxes with lower levels of carcinogenic cyclic compounds. However, other plastics including PVC (Polyvinyl Chloride) and PA (Polyamide) can be harmful when melted. Additionally, benzene, a confirmed human carcinogen, as well as probable carcinogens styrene and ethylbenzene, are among the hazardous cyclic compounds found in fumes from melting ABS and PS. Fume generation varies depending on plastic type, formulation, and processing conditions (Unwin et al., 2010) Table 7.

Different types of fumes are detected using different digital metres. Detectors for different types of fume are analysed and presented below:

i. VOC Detectors

Volatile Organic Compounds (VOCs) pose significant dangers, with immediate effects including severe irritation to the eyes, nose, and lungs. Prolonged exposure to fumes from synthetic plastics without proper safety precautions can lead to serious health issues including cancer, birth defects or hormonal disruptions Figure 13.

PID detector (Photoionisation Detector) is recommended. This detector helps measuring the levels of VOCs and assessing fume safety levels.

ii. Benzene Sensors

Benzene, another type of volatile organic compound (VOC), is frequently present in industrial processes including plastic production and recycling. To uphold workplace safety, monitoring benzene levels is essential. Implementing benzene sensors is a proactive measure to detect and manage potential hazards.

iii. Carbon Monoxide (CO) Detectors

Carbon monoxide (CO), hydrogen sulphide, hydrochloric acid and carbon dioxide are potential hazards in industrial processes, particularly in plastic production and recycling. Carbon monoxide when inhaled gets mixed with blood and creates carboxyhemoglobin which deteriorates oxygen carrying capacity of blood. Hence, monitoring the levels of these gases is crucial for safeguarding the safety of workers.

Table 8 *WHO Pollutants guidelines*

Pollutant	Critical outcome(s) for guideline definition	Guidelines	Comments
Benzene	• Acute myeloid leukaemia (sufficient evidence on causality) • Genotoxicity	• No safe level of exposure can be recommended • Unit risk of leukaemia per 1 µg/m3 air concentration is 6 × 10-6 • The concentrations of airborne benzene associated with an excess lifetime risk of 1/10 000, 1/100 000 and 1/1 000 000 are 17, 1.7 and 0.17 µg/m3, respectively	
Carbon monoxide	Acute exposure-related reduction of exercise tolerance and increase in symptoms of ischaemic heart disease (e.g. ST-segment changes)	• 15 minutes - 100 mg/m3 • 1 hour - 35 mg/m3 • 8 hours - 10 mg/m3 • 24 hours - 7 mg/m3	
Formaldehyde	Sensory irritation	0.1 mg/m^3 - 30-minute average	The guideline (valid for any 30-minute period) will also prevent effects on lung function as well as nasopharyngeal cancer and myeloid leukaemia
Naphthalene	Respiratory tract lesions leading to inflammation and malignancy in animal studies	0.01 mg/m^3 - annual average	The long-term guideline is also assumed to prevent potential malignant effects in the airways
Nitrogen dioxide	Respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation and decreases in immune defence, leading to increased susceptibility to respiratory infection	• 200 µg/m3 - 1 hour average • 40 µg/m3 - annual average	No evidence for exposure threshold from epidemiological studies
Polycyclic aromatic hydrocarbons	Lung cancer	• No threshold can be determined and all indoor exposures are considered relevant to health • Unit risk for lung cancer for PAH mixtures is estimated to be 8.7 × 10^{-5} per ng/m^3 of B[α]P • The corresponding concentrations for lifetime exposure to B[α]P • producing excess lifetime can cer risks of 1/10 000, 1/100 000 and 1/1 000 000 are approximately 1.2, 0.12 and 0.012 ng/m^3, respectively	B[α]P is taken as a marker of the PAH mixture

b. Air Ventilation

Proper air distribution and ventilation are essential for maintaining safe, breathable atmospheres where gases are generated. Key goals include removing harmful gases, preventing flammable or toxic concentrations, and ensuring fresh air supply. Proper duct sizing is required to maintain airflow patterns, ensuring uniform air distribution and healthy indoor air quality.

Indoor Air Quality (IAQ) standards define permissible concentrations of contaminants, pollutants, and ventilation parameters within enclosed spaces. These standards vary by industry sector, building type, and geographical location, and are established by various authorities and organizations. Notably, the Occupational Safety and Health Administration (OSHA) defines permissible exposure limits (PELs) for airborne substances in occupational settings, while the World Health Organization (WHO) issues comprehensive global IAQ guidelines. Regional, municipal, and industry-specific standards may also apply.

The table Table 8 summarizes key pollutants from the "WHO Guidelines for Indoor Air Quality: Selected Pollutants" (WHO, 2010).

c. Fumes control and filters

Efficient management of fumes necessitates the installation of local exhaust ventilation systems at emission sources, such as extruders and injection moulding machines, to capture and control fumes preemptively before their release into the workplace. The ventilation capacity is quantified through the air exchange rate, denoted as Air Changes per Hour (ACH), reflecting how frequently the air within a designated space is replenished with fresh air within an hour.

In the context of fume filtration, both standalone filters and activated carbons are proven to be effective. **Standalone filters** are affixed to centrifugal fans for ventilation. The Optimal usage conditions are humidity levels below 70% and ambient temperatures lower than 80°C.

The utilisation of **activated carbon filters** (ACF) represents a cleanest and straightforward filtration method so far. Distinguished by its extensive surface area and treated porous structure, ACF facilitates effective fume capture. Notably, it excels in removing various volatile organic compounds (VOCs) and gases, including but not limited to toluene, xylene, styrene, alcohol, benzene, decane, ethylbenzene, heptane, octane, pentane, acetone, and hexane (Bolourani et al., 2008). Despite being a cost-effective adsorbent, activated carbon does have limitations, such as the potential for fire hazards and reduced selectivity (Amano, 2010). The olfactory detection of breakthrough compounds serves as an indicator for timely filter replacement. An iodine number exceeding 1050mg/g is indicative of superior active surface area and consequently enhanced filtration.

Safety Assessment Check Points

1	Safety in Preprocessing	Inspect waste for sharp objects, contamination, and biohazards.
		Ensure all workers wear PPE (gloves, masks, aprons, safety shoes, goggles).
		Set up separate sorting lines for PET, PE, PP, and non-recyclables.
		Provide ergonomic tools to reduce repetitive strain.
		Verify wastewater handling meets hygiene and environmental standards.
2	Managing Risks in Plastic Forming	Check ventilation systems and airflow.
		Confirm hopper lids are closed after loading pellets.
		Monitor fumes at nozzles, moulds, and extrusion points.
		Review temperature logs to avoid overheating.
		Install fume detectors (VOC/PID, benzene, CO) near machines.
3	Selecting Safe Locations	Ensure the site is away from residential areas.
		Confirm quick access for emergency services.
		Assess transport access for workers and materials.
		Conduct an Environmental Impact Assessment (EIA).
		Document community impact and mitigation measures.
4	Designing Facility Layout	Maintain safe clearance around all machines.
		Minimise hot-material handling distance.
		Ensure lighting meets national illumination standards.
		Position electrical outlets to prevent overloads or short circuits.
		Mark and keep evacuation routes clear.
5	Maintaining Equipment & Machines	Conduct machine-specific risk assessments annually and after changes.
		Test emergency stop buttons weekly.
		Display and train staff on SOPs (start-up, operation, shutdown, maintenance).
		Maintain a documented maintenance schedule with assigned responsibility.
		Inspect guards and interlocks for damage or tampering.

6	Handling Material	Store materials in labelled and protected areas.
		Avoid mixing incompatible plastic types.
		Check working conditions (heat, humidity, ergonomics).
		Provide proper material-handling equipment (trolleys, gloves, steel-toe boots).
		Inspect storage containers for contamination or damage.
7	Protecting Workforce	Deliver role-specific safety training.
		Maintain a clear hazard reporting system.
		Monitor and control noise, smoke, and dust.
		Ensure PPE availability, fit testing, and replacement schedules.
		Record incidents and conduct root-cause analyses.
8	Preventing Fire	Install fire detectors and alarms suited for plastic processing.
		Inspect electrical systems monthly.
		Separate flammable materials from heat sources.
		Conduct fire drills at least twice a year.
		Maintain fire extinguishers and ensure access.
9	Environmental Safeguards	Develop a waste management plan, including hazardous waste.
		Prohibit burning or uncontrolled dumping of plastic.
		Install pollution control measures (e.g., filtration, wastewater treatment).
		Monitor compliance with local environmental regulations.
		Record noise and emission control actions.
10	Gas & Fume Management	Identify plastic types and associated fume risks.
		Install detectors for VOCs, benzene, CO, and other gases.
		Ensure ventilation meets required ACH levels.
		Use activated carbon or standalone filters; replace when breakthrough is detected.
		Test indoor air quality and recalibrate detectors regularly.

Summary

Plastic recycling process poses a number of specific potential hazards through the stages. Understanding the hot spots and ensuring the necessary measures in place will minimise the preventable accidents and incidents, and help the industry flourish and address the environmental, social and economic sustainability of the plastic recycling sector.

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