LIFE CYCLE ASSESSMENT OF PLASTIC WASTE INCINERATION AT END-OF-LIFE

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Abstract – The ongoing development and expanding use of new plastic polymers have intensified global challenges in plastic waste management. Incineration has gained rapid popularity due to its advantages of significantly reducing waste volume and utilizing the high calorific value of plastics for thermal energy and electricity generation; however, these benefits come with environmental trade-offs. Because conventional incinerators process mixed waste streams, the net environmental impact attributable specifically to plastic waste and to individual plastic types has remained unclear. This study therefore conducts a comparative assessment of five major plastics: PET, PE, PP, PS, and PVC. Two extended system boundaries are examined: one incorporating pollution-control measures necessary to comply with U.S. regulatory standards, and the other integrating energy recovery. Using a functional unit of 1 tonne of plastic waste, inventory analysis and impact assessment were performed using the TRACI 2.2 method. Results indicate that environmental impacts are primarily driven by the input inventories required for pollutant control during incineration of each plastic type, while energy recovery substantially reduces impacts when reduced-burden allocation is applied. Ten impact categories were evaluated to determine the relative viability of each plastic type. These findings provide decision-support for local authorities and stakeholders by identifying which plastic materials may be more suitable or less desirable for incineration, depending on regional environmental priorities and vulnerabilities.

Keywords: Plastic Waste, Incineration, LCA, Environmental Impact Assessment, Waste Management

1. Introduction

The development of modern plastics dates back to 1839, further advances in polymer chemistry led to the identification of polyvinyl chloride (PVC) in the late nineteenth century, and with growing global interest in synthetic polymers, an additional set of plastics including polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) was developed during the first half of the twentieth century. Collectively, these five major plastic categories account for approximately 90% of total global plastic demand (Andrady and Neal, 2009). With rapid urbanization, and versatile nature of plastics supported for global consumption of plastic products increasing dramatically, yet chemical composition of plastic created technological challenges and renders their recovery from municipal solid waste (MSW) economically unattractive (Chow et al., 2017; Idumah et. al., 2019). Without effective management strategies, these wastes are ultimately disposed of on land, and their non-biodegradable nature leads to long-term impacts on both ecosystems and human health.

Seay and Ternes (2022) criticize that loopholes within governing bodies have rendered regulations ineffective in controlling plastic waste emissions, particularly by failing to address the root issue of plastic waste generation during the manufacturing process. U.S. environmental laws regulate

pollutants based on specific chemical hazards, such as toxicity, reactivity, ignitability, and corrosivity, and are organized around media like air, water, and waste. However, because plastic waste is chemically inert and lacks these hazard characteristics, it falls outside federal hazardous pollutant regulations, is categorized as municipal waste, and is regulated inconsistently by states, with no direct, comprehensive federal regulation of plastic as a pollutant. In contrast, researchers (Aiguobarueghian et al., 2024; Hart, 2021) argue that the development of legislative measures addressing the plastic waste crisis, together with federal regulations for managing hazardous and non-hazardous waste and state-level initiatives banning certain types of plastics, plays a significant role in shaping plastic waste management. This situation raises concerns about the coordination among regulatory bodies in implementing a strategic, nationwide plan; a collaborative effort involving federal and state governments, industry stakeholders, and the public is crucial to address the entire lifecycle of plastic waste and achieve sustainable management (Etukudoh et al., 2024).

Several studies suggest controlling plastic waste through legislative actions such as bans on certain types of plastics (Wang et al., 2022; Rose, 2020). In contrast, a life cycle assessment by Meng et al. (2024) revealed that replacing plastics with alternative materials could increase greenhouse gas emissions by 10–90%, indicating that eliminating plastics from daily life is not a viable solution; instead, efforts should focus on the sustainable use of plastic products.

Several research are conducted to identify effective methods of plastic waste emissions. Panda et al. (2010) identified several plastic-waste management methods, including landfilling, mechanical recycling, biological recycling, and thermochemical recycling. Rigamonti et al. (2014) continued their search to compares five different approaches for plastic waste management including combined recycling and incineration system with sorting facility. Damayanti et al. (2022) regarded chemical and mechanical recycling as simple, low-cost, and environmentally friendly approaches, emphasizing that integrating recycling with effective plastic-waste separation is essential for reducing environmental burdens.

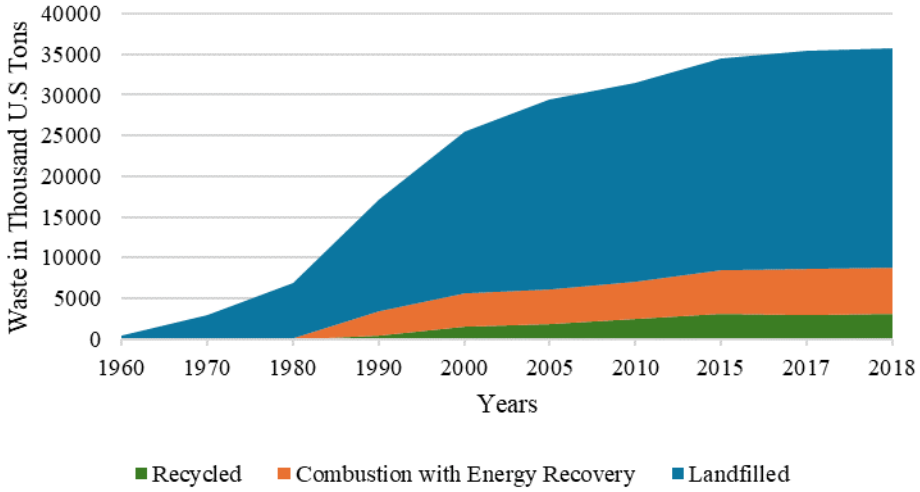

Figure 1: Municipal Plastic Waste Management in the U.S.A (U.S EPA, 2025)

Despite extensive efforts to promote environmentally friendly waste-management practices in the United States, landfill disposal has continued to increase. Although the use of recycling and

incineration has risen slightly, landfilling still remains the dominant waste-management approach (Figure 1).

2. Literature Review

Effective plastic waste management remains a critical global challenge due to the durability and volume of synthetic polymers in municipal waste streams. Incineration, despite being positioned lower in the waste management hierarchy compared to recycling and reuse, continues to play a significant role in energy recovery and volume reduction of plastic waste. The following review synthesizes previous research relevant to plastic waste incineration, encompassing aspects of waste distribution, combustion behavior, emission control, and post-incineration treatment technologies.

Milbrandt et al. (2022) analyzed the distribution of plastic waste across the United States and reported that plastics account for 10–18% of municipal solid waste, depending on the region. Their study revealed that polyethylene (PE, including both HDPE and LDPE) constitutes 52% of total plastic waste, of which 85% ends up in landfills, 15% is recycled, and only 10% is incinerated. Similarly, polyethylene terephthalate (PET) represents 14% of plastic waste, with 76% disposed of in landfills, 15% recycled, and 9% incinerated. Polypropylene (PP) was also identified as a major category, accounting for 19% of plastic waste, among which 88% is landfilled, 3% recycled, and 9% incinerated. Polystyrene (PS/EPS), polyvinyl chloride (PVC), and other plastics (such as PC, Nylon, ABS, and PLA) collectively represent 7%, 2%, and 7% of the municipal plastic waste stream, respectively, with only 9% of their total disposal occurring through incineration. Overall, the study concluded that approximately 86% of plastic waste in the U.S. is landfilled, 9% is incinerated, and only 5% is recycled.

Similarly, Jin et al. (2024) identified PE and PP as the most commonly produced and utilized polymers worldwide. Their study on microplastic generation from plastic burning revealed emissions ranging from 1.9 to 565 n/kg, and it was suggested that pre-separation of plastic waste prior to incineration can significantly reduce microplastic formation.

Ágnes and Rajmund (2016) described incineration as a widely adopted method of plastic waste management involving the combustion of plastics, with the resulting heat used to power cement factories and generate electricity. Although they acknowledged the energy recovery benefits, they emphasized that incineration occupies the lower tiers of the waste management hierarchy and is not considered the most sustainable solution due to emission-related concerns. Similarly, Webb et al. (2012) recognized incineration as an efficient disposal technique requiring minimal land space while facilitating energy recovery in the form of heat. However, they raised concerns over the formation of harmful components and greenhouse gas emissions during the process.

Expanding on comparative waste management options, Foolmaun and Ramjeawon (2008) conducted a life cycle assessment (LCA) of PET waste under three disposal scenarios - landfill, combined landfill-incineration (50:50), and full incineration. Their findings demonstrated that incineration exhibited lower environmental impacts compared to landfilling, identifying it as a more efficient waste management alternative. Similarly, Mazhandu et al. (2020) recommended incineration for plastic waste contaminated with organic matter, arguing that recycling such mixed waste leads to down cycling and increased demand for virgin plastic production, thereby heightening upstream environmental burdens.

The combustion behavior of plastics has also been extensively studied to optimize incineration efficiency and emission control. Wheatle et al. (1993) conducted bench-scale experiments on the combustion of selected plastics and their emission of polycyclic aromatic hydrocarbons (PAH). They reported that at 750°C, polyethylene undergoes pyrolytic degradation with incomplete combustion, while at 950–1150°C, full ignition and post-flame thermal destruction occur—conditions identified as optimal for effective combustion. Similarly, Singh et al. (2019) investigated thermal degradation under non-isothermal pyrolysis, finding that liquid yield increases with temperature until it peaks, then declines due to the formation of lighter hydrocarbon gases at extreme temperatures.

Mentes et al. (2023) further analyzed combustion behavior using thermoanalytical derivatography and revealed that plastics composed of aliphatic compounds, such as PET, decompose at lower temperatures than those containing aromatic structures like HDPE. Aliphatic polymers melt and fragment upon heating, while aromatic compounds undergo volatilization followed by macro-decomposition into gases. Complementing these findings, Kasmuri et al. (2022) demonstrated that higher combustion temperatures increase micro plastic formation for PP and PVC, whereas higher airflow rates decrease micro plastic yield. Jin et al. (2024) supported this conclusion, showing that incineration temperature and air flow are critical determinants of micro plastic release during combustion.

In terms of emission control, Chen and Huang (2007) explored CO_2 emissions from plastic waste incineration using modified O_2/recycled flue gas (RFG) combustion technology. Their results indicated that increasing oxygen concentration in the feed gas decreases CO_2 formation, while NO_x emissions rise under low O_2 concentrations (<40%) with increased RFG ratios but decrease under high O_2 concentrations (>60%). These findings highlight the importance of combustion atmosphere control in balancing energy efficiency and emission reduction.

The environmental trade-offs between recycling and incineration were evaluated by Merrild et al. (2012), who compared various municipal waste management options. Their results revealed that recycling paper, aluminum, glass, and steel provides greater environmental benefits, whereas plastics and cardboard are better managed through incineration due to reduced collection, pre-treatment, and energy recovery impacts.

Chin et al. (2005) identified hydrochloric acid (HCl) as a prevalent pollutant in the flue gas of municipal and hazardous waste incinerators and found that hydrated lime [$Ca(OH)_2$] effectively removes acidic gases such as HCl, SO_2, and CO_2. They also reported that the presence of HCl enhances the removal efficiency of SO_2 and CO_2. Supporting this, NTEPA (2003), A&C Plastic Inc. (n.d), and Plastik City (n.d) reported that common plastics such as PET, HDPE, LDPE, PP, PVC, and PS have ignition points between 330°C and 410°C, suggesting that segregation of plastic types before incineration can improve combustion efficiency and energy recovery.

The incineration of plastic waste involves several interconnected processes, including flue gas purification, desulfurization, and wastewater treatment. Each stage employs specific physicochemical principles designed to mitigate emissions and minimize environmental impacts.

Early research on DeNOx technology emphasized the role of ammonia in reducing nitrogen oxide emissions from incineration processes. Lyon (1987) conducted experimental studies showing that mixing ammonia (NH_3) with flue gas significantly enhances thermal DeNOx efficiency. In addition to reducing NO_x, ammonia reacts with sulfur trioxide (SO_3) to prevent the formation of sulfuric acid (H_2SO_4) during cooling, forming ammonium sulfite ($(NH_4)_2SO_3$) or ammonium bisulfate (NH_4HSO_4). It also inhibits hydrochloric acid (HCl) mist formation by converting it into ammonium chloride (NH_4Cl).

With technological advancements, Selective Catalytic Reduction (SCR) systems, also known as NH_3-SCR, have been widely implemented. Jeon (2023) reported that the incorporation of vanadium oxide (V_2O_5) as a catalyst significantly enhances NO_x reduction efficiency, while Mizuguchi (2001) demonstrated that at 300–500°C, titanium dioxide (TiO_2) generates thermally excited electron–hole pairs that decompose volatile organic compounds (VOCs), as also confirmed by Shinbara et al. (2005).

The subsequent stage of gas treatment targets sulfur dioxide (SO_2) removal through neutralization. Gottschalk et al. (1996) compared sorbents and identified calcium hydroxide ($Ca(OH)_2$) and limestone ($CaCO_3$) as cost-effective alternatives to caustic soda (NaOH), making quicklime (CaO) the preferred reagent for desulfurization. The reaction produces calcium sulfate ($CaSO_4$, gypsum) as a reusable byproduct. Moreover, caustic soda (NaOH) used in desulfurization forms sodium sulfite (Na_2SO_3), which reacts with quicklime (CaO) to regenerate NaOH while producing $CaSO_4$. This cyclic reaction minimizes NaOH consumption and enhances process sustainability.

Baloyi et al. (2024) demonstrated the efficiency of water scrubbers for CO_2 absorption, showing that one liter of water can capture approximately 0.3 kg of CO_2. Their findings, though developed for coal plants, are applicable to incineration systems using similar scrubbing mechanisms.

Finally, wastewater from flue gas cleaning is treated through coagulation and chemical purification. Pernitsky and Edzwald (2006) emphasized coagulation as a key physicochemical process, with poly-aluminum coagulants showing superior performance. Similarly, ferric chloride ($FeCl_3$) has been recognized as effective in removing heavy metals and odors (Ridge & Sedlak, 2004; Solmaz et al., 2024; Prathna & Srivastava, 2021). Hydrochloric acid (HCl) is commonly used to remove organic and inorganic impurities (Vogel & Adam, 2011; Pietrelli et al., 2018; Prazeres et al., 2019), while triazine compounds react with hydrogen sulfide (H_2S) to form stable, non-toxic thiadiazine derivatives (GeoCon, 2025), ensuring treated effluents meet environmental discharge standards.

Several studies have highlighted the benefits of incineration and documented the various emissions associated with burning municipal solid waste. However, a comparative assessment focusing specifically on the incineration of different plastic types has not been conducted. Although existing research provides technological frameworks for individual pollution-control units, there remains a need for an integrated study that examines how a complete purification system performs within an incineration facility and how it influences the overall environmental outcome. Furthermore, LCA of different plastic types under identical incineration conditions are largely absent in the current literature. This study aims to address these research gaps by evaluating the environmental impacts of incinerating plastics based on their material type.

3. METHODOLOGY

This study evaluates the environmental impacts associated with the incineration of plastic waste using life cycle inventory (LCI) approach. The operational mechanism of the incineration process is established based on previous studies (Wheatle et al., 1993; Chin et al., 2005; Lyon, 1987; Jeon, 2023; Gottschalk et al.,1996; Baloyi et al., 2024) while ensuring compliance with applicable environmental legislation. In the United States, the Clean Air Act (CAA) serves as the primary federal statute governing air pollution control (EPA, 2024). The Act authorizes the U.S. Environmental Protection Agency (EPA) to establish emission limits for pollutants such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2).

Under the EPA's New Source Performance Standards r – 40 CFR Part 60, Subparts Ea, Eb, and Cb – municipal waste combustors are required to install Selective Non-Catalytic Reduction (SNCR) or Selective Catalytic Reduction (SCR) systems to mitigate NO_x emissions (U.S. EPA, 2022). These regulatory requirements necessitate the integration of DeNOx technologies, which form a core component of the incineration process.

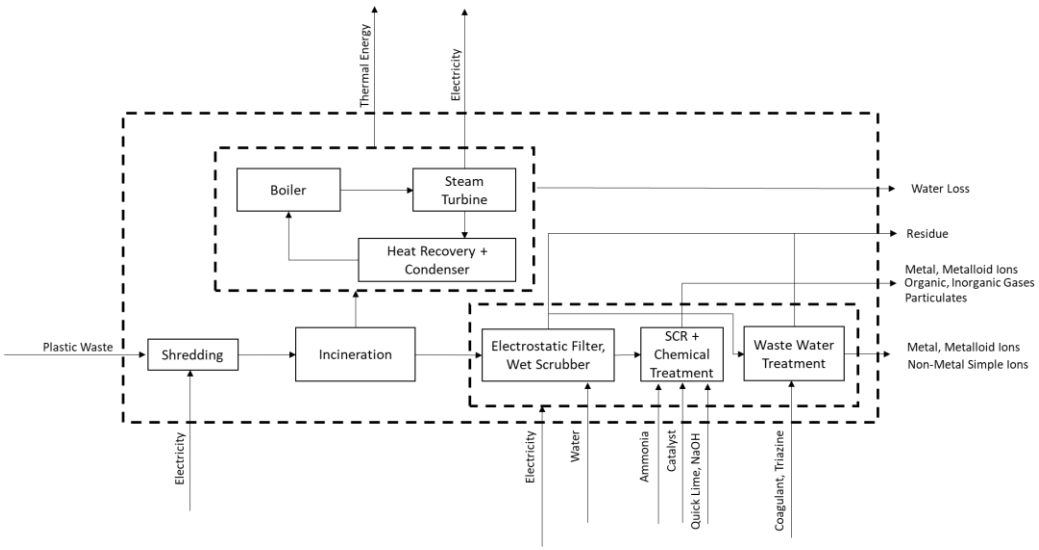

Figure 2: Incineration System Boundary

As presented in Figure 2, the overall incineration system can be divided into three sequential stages: (1) plastic combustion, (2) flue gas treatment, and (3) wastewater treatment. The present study assumes the availability of pre-segregated plastic waste at the incineration facility, as including collection and sorting processes would introduce additional uncertainty and alter environmental allocation. Future research may extend this framework by incorporating regional waste collection centers and alternative treatment pathways. The current analysis, however, focuses exclusively on the environmental impact of the incineration process itself.

3.1 Plastic Combustion

In the first stage, segregated plastic waste is fed into a rotary kiln, where high-temperature combustion generates flue gas and thermal energy. While pure polymer combustion ideally

produces no ash, the presence of fillers, dyes, and additives in commercial plastics leads to the formation of bottom ash residues.

Thermal energy recovered from the kiln is transferred through embedded pipe coils to superheat water in a boiler, producing high-pressure steam that drives a steam turbine to generate electricity. Although residual heat can be utilized for district heating or industrial processes, this study considers only the portion allocated to electricity generation for environmental impact evaluation.

3.2 Flue Gas Treatment

The second stage involves multi-step purification of the flue gas. Initially, an electrostatic precipitator (ESP) removes fine particulate matter and dust. The cleaned gas then enters the Selective Catalytic Reduction (SCR) system for NO_x removal.

In the SCR process, ammonia (NH_3) in hydrous form is injected into the flue gas stream, where it reacts with nitrogen oxides over a vanadium pentoxide (V_2O_5) catalyst supported on titanium dioxide (TiO_2). The overall reduction of NO_x follows:

$$4NO+4NH_3+O2 \rightarrow 4N_2+6H_2O$$

At startup, an external heat source (typically natural gas) is used to initiate the reaction, but once steady combustion is achieved, the kiln's thermal energy sustains the reaction temperature. As life cycle data for V_2O_5 were unavailable, chromium trioxide (CrO_3) was adopted as a proxy in impact modeling. Additionally, TiO_2 contributes to the oxidation of volatile organic compounds (VOCs) through high-temperature photocatalytic reactions.

For sulfur dioxide (SO_2) removal, a two-step alkaline scrubbing mechanism is applied. In the first step, SO_2 reacts with caustic soda (NaOH) to form sodium sulfite (Na_2SO_3):

$$2NaOH+SO_2 \rightarrow Na_2SO_3+H_2O$$

In the second step, quicklime (CaO) reacts with the formed sodium sulfite, regenerating sodium hydroxide while producing calcium sulfite ($CaSO_3$):

$$Na_2SO_3+CaO+H_2O \rightarrow 2NaOH+CaSO_3$$

The regenerated NaOH re-enters the scrubbing cycle, enhancing reagent efficiency and minimizing chemical consumption. Subsequent oxidation of calcium sulfite yields gypsum ($CaSO_4 \cdot 2H_2O$) as a stable byproduct:

$$CaSO_3+12O_2+2H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

This cyclical reaction chain demonstrates a closed-loop desulfurization mechanism, reducing both reagent demand and waste generation.

Finally, water scrubbing is used to absorb carbon dioxide (CO_2) and soluble acidic gases, while simultaneously capturing remaining fly ash and fine particles. The resultant scrubber sludge and contaminated water are then directed to the wastewater treatment stage.

3.3 Wastewater Treatment

The third stage involves the treatment of wastewater originating from the scrubbing process. Chemical coagulants, including alum ($Al_2(SO_4)_3$) and ferric chloride ($FeCl_3$), are used to promote flocculation and sedimentation of suspended solids. Subsequently, hydrochloric acid (HCl) is added to remove residual inorganic and organic impurities.

To neutralize acidic content, triazine compounds are introduced, which react with acidic components to form non-toxic, stable ammonium-type products. The generalized neutralization reaction can be represented as:

$$R_3N + H^+ \rightarrow R_3NH^+$$

where R_3N denotes the triazine base that binds free protons, producing neutralized effluents suitable for discharge or reuse within the facility.

3.4 Data Source

All technologies, chemical pathways, and process parameters considered in this analysis are derived from datasets developed by Mattia Clementi and the Ecoinvent 3.10 (FitzGerald et al. 2023).

4. RESULTS

The incineration process was modeled within three system boundaries: combustion, power generation, and emission control. The inputs and outputs associated with these system boundaries were evaluated for the incineration of five types of plastic waste. Since each plastic type possesses distinct physical and chemical properties, the resource requirements for their combustion differ accordingly.

Plastic waste generally contains a small proportion of moisture; therefore, its dry mass is slightly lower than its wet mass. As illustrated in Figure 3, PP exhibits the highest moisture content at 15.4%, corresponding to a dry mass of 0.841 kg per kilogram of wet mass. Other plastics, such as PET, PS, and PVC, contain approximately 0.2% moisture, while PE has about 0.4% moisture. Among the analyzed polymers, PS exhibited the highest carbon content at 0.87 kg C per kilogram of dry mass, whereas PVC showed the lowest. The net heating value was also found to vary across polymers, with PE demonstrating the highest value of 39.16 MJ/kg, and PVC having the lowest among the five plastic types.

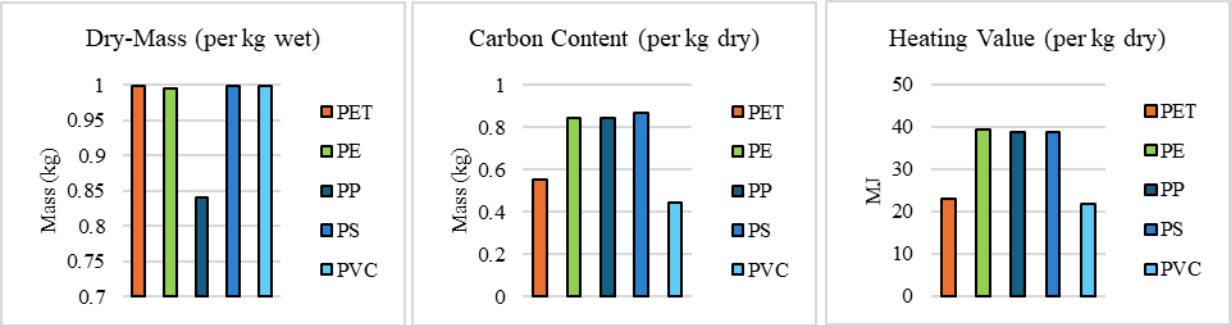

Figure 3: Physical Properties of Plastic Waste

4.1 Inventories

Oxygen plays a critical role in the combustion of plastic waste and in the subsequent oxidation of flue gases. The net oxygen demand per kilogram of waste combusted is defined as the total oxygen input minus the unreacted oxygen emitted in the flue gas. As presented in Table 1, O_2 constitutes the major component, with quantities ranging from 3,259 kg for PET to 6,749 kg for PE per functional unit. This pattern reflects the direct relationship between oxygen consumption and the heating value of plastics; polymers with higher carbon content and calorific value, such as PE (39.16 MJ/kg) and PP (38.75 MJ/kg), require greater oxygen input for complete oxidation and energy recovery. In contrast, PET and PVC exhibit comparatively lower oxygen demand due to their reduced energy potential and the presence of oxygen or chlorine in their molecular structures, which limits further oxidation.

Table 1: Summary of Input for 1 Tonne Plastic Incineration

Input Substances	**Unit**	**PET**	**PE**	**PP**	**PS**	**PVC**
Oxygen (O_2)	Kg	3259.224	6749.404	5699.000	5811.475	3347.213
Ammonia Anhydrous (NH_3)	Kg	0.661	0.624	0.527	0.616	0.351
Chemical Inorganic (Ch.I)	Kg	0.055	0.095	0.080	0.092	14.065
Cr_2O_3 (V_2O_5 equivalent)	Kg	0.002	0.001	0.001	0.001	0.001
Hydrochloric Acid (HCl)	Kg	0.012	0.020	0.017	0.020	2.987
Ferric Cloride ($FeCl_3$)	Kg	0.189	0.328	0.277	0.089	0.084
Quick Lime (CaO)	Kg	0.442	0.805	0.680	0.708	252.630
Caustic Soda (NaOH)	Kg	0.124	0.294	0.248	0.337	44.369
Titanium Dioxide (Ti_2O_3)	Kg	0.051	0.024	0.041	0.048	0.027
Triazine Compound (R^+)	Kg	0.002	0.010	0.008	0.020	0.016
Decarbonized H_2O	Kg	97.786	167.867	141.743	192.031	24921.459

Ammonia (NH_3) is consumed as part of the DeNOx process to reduce nitrogen oxides (NO_x) in flue gases, with usage ranging between 0.35 and 0.66 kg across polymers. Slightly higher ammonia consumption in PET and PS can be attributed to higher NO_x generation during combustion of oxygenated plastics. Cr_2O_3, used here as a substitute reference for vanadium-based SCR catalysts, shows minimal consumption (<0.002 kg), representing a catalytic rather than stoichiometric role. Ch.I and HCl serve as treatment and neutralization agents for specific pollutants. PVC records notably higher consumption of both Ch.I and HCl, corresponding to its high chlorine content and

the formation of acid gases (HCl, Cl_2) during combustion. These emissions necessitate intensive scrubbing and chemical stabilization, unlike polyolefins (PE and PP), which contain no halogens and hence require substantially less acid treatment.

$FeCl_3$, used in coagulation for wastewater purification, exhibits moderate variation, ranging from 0.084 kg (PVC) to 0.328 kg (PE). Its demand correlates with the production of metal-laden residues and suspended particulates in scrubber effluents. Similarly, CaO and NaOH are used in flue gas desulfurization and acid neutralization. PVC again shows a disproportionately high requirement: 252.63 kg of CaO and 44.37 kg of NaOH, indicating extensive use of alkaline reagents to neutralize acidic species generated during its combustion. In contrast, the other polymers show minimal lime and soda requirements (<1 kg), consistent with their low sulfur and chlorine content.

Ti_2O_3 functions primarily as a photocatalyst in the oxidation of VOCs, with consumption remaining relatively uniform (0.02–0.05 kg) across all polymer types. R^+, responsible for hydrogen sulfide removal, show minimal variation, with values between 0.002 and 0.020 kg, reflecting trace-level H_2S formation during incineration.

Finally, decarbonized water is used extensively as a scrubbing medium for CO_2 and other soluble gases. While non-halogenated plastics (PET, PE, PP, PS) require between 97 and 192 kg of water per unit, PVC demonstrates an extremely high consumption of 24,921 kg, owing to the additional cooling and washing cycles required to capture acidic and chlorinated compounds in the flue gas stream.

In overall, PE and PS require higher oxidative and catalytic inputs for efficient combustion, while PVC imposes greater chemical demand for post-combustion neutralization.

Table 2 summarizes various Emissions from industrial processes are categorized according to their environmental compartments: air, water, and land. Metals and their ions, originating from impurities, catalysts, and the degradation of incineration plant components, constitute a relatively small fraction of total emissions. These metals range from less hazardous species, such as calcium, aluminum, iron, cobalt, manganese, and sodium, to non-carcinogenic but potentially harmful metals like barium, chromium, and copper, and extend to carcinogenic metals, including lead, mercury, cadmium, and nickel. Similarly, metalloids include ecotoxic elements such as antimony and carcinogenic elements such as arsenic. Non-metal elements, such as bromine and cyanide, are also present in the emissions.

Inorganic gases account for the largest proportion of total emissions. Carbon dioxide (CO_2) and carbon monoxide (CO) are the primary greenhouse gases, and their emissions have been significantly reduced through decarbonization measures. Nitrogen compound gases, including nitrous oxide (N_2O) and nitrogen oxides (NO_x), are limited due to the implementation of $DeNO_x$ technologies. Any unreacted ammonia (NH_3) from the $DeNO_x$ process is also emitted, although in relatively minor quantities. Inorganic toxic gases, such as sulfur dioxide (SO_2), hydrochloric acid (HCl), and hydrogen fluoride (HF), are effectively mitigated through flue gas scrubbing; however, complete normalization of these emissions is not fully achievable. Particulate matter, both fine (<2.5 μm) and coarse (2.5–10 μm), is also released into the atmosphere.

During flue gas treatment, a portion of gaseous emissions can dissolve or mix with water, eventually entering water bodies. In this study, biological oxygen demand (BOD_5) and chemical oxygen demand (COD) were observed to be nearly identical, indicating that oxidizable inorganic compounds are present only in negligible amounts, with total organic carbon (TOC) serving as the primary contributor to oxygen demand.

Solid residues, including bottom ash from incineration and sludge from scrubbers, are disposed of on land. Although complete combustion of plastics theoretically produces no residue, incomplete combustion and the presence of inorganic compounds prevent total oxidation. Additionally, fly ash generated during combustion contributes further to solid waste.

All the plastics analyzed contained relatively low quantities of metals, metalloids, and non-metals. In contrast, significant differences were observed in the emission of inorganic gases among the different plastic types. PS exhibited the highest quantities of inorganic gases, whereas polyvinyl chloride PVC showed the lowest emissions, which corresponds to their respective carbon content as presented in Figure 3. Unlike non-halogenated plastics, PVC contains halogen atoms, and its combustion produces substantial amounts of toxic inorganic gases, such as hydrogen chloride HCl and HF. Moreover, PVC combustion resulted in elevated emissions of non-metals to water, particularly chloride ions (Cl^-), which can combine with water during scrubbing to form acidic effluents.

Table 2: Summarizes emission from Incineration of 1 functional unit

Emissions	Unit	PET	PE	PP	PS	PVC
Emission to air						
Metals	kg	0.0425	0.0823	0.0695	0.0198	0.0210
Metalloids Ions	kg	1.48E-05	1.37E-05	1.16E-05	1.45E-05	1.57E-05
Non-Metal Elements	kg	1.13E-04	3.38E-05	4.34E-05	4.85E-04	1.17E-04
Inorganic Gases	kg	2018.320	3072.354	2594.219	3165.747	1606.093
Organic Compound	kg	0.00166	0.00018	0.00061	0.00061	0.00164
Inorganic Toxic Gases	kg	0.02122	0.00318	0.00268	0.00697	0.27472
Particulates Matter	kg	0.00323	0.00035	0.00118	0.00119	0.00320
Emission to Water						
Metals	kg	0.01457	0.03254	0.02743	0.01214	0.01310
Metalloids Ions	kg	1.28E-07	8.31E-09	7.01E-09	3.34E-08	3.63E-08
Non-Metal and Simple Ions	kg	0.61124	1.12386	0.95040	1.2071	317.281
Oxygen Demand	kg	0.65300	0.96700	0.81700	0.9970	0.50600
Total Organic Carbon (TOC)	kg	0.27800	0.42300	0.35700	0.43600	0.22100
Emission to Land						
Ash & Residue	kg	20.334	32.417	27.372	30.321	253.760

Similarly, ash collected from the electrostatic precipitator and residues from the scrubber account for a significant proportion by weight. Among the plastics studied, PET produced the least solid waste, indicating that it burns more completely. PP, PS, and PE generate solid waste in increasing order, while PVC produces the highest amount. The complex molecular structure of PVC makes it difficult to thermally decompose. Saeed (2004) suggested that 100% PVC should undergo a two-

stage combustion process, with the temperature in the second stage significantly higher than in the first reactor to effectively decompose the coke, which consists of carbon, hydrogen, and chlorine.

4.2 Impact Assessment

The impact analysis in this study was conducted using the TRACI 2.2 method, which is the life cycle impact assessment framework adopted by the U.S. EPA. Three distinct methods of plastic-waste management were examined, and each waste type demonstrated its own specific impact profile. As incineration process produces thermal energy, some portion of which applies for electricity generation. The analysis applies an impact-reduction approach, which accounts for the decreased environmental burden associated with the value returned from the facility to the base system. The impacts associated with five different types of plastic subjected to incineration were identified, and the resulting impact profiles were compared.

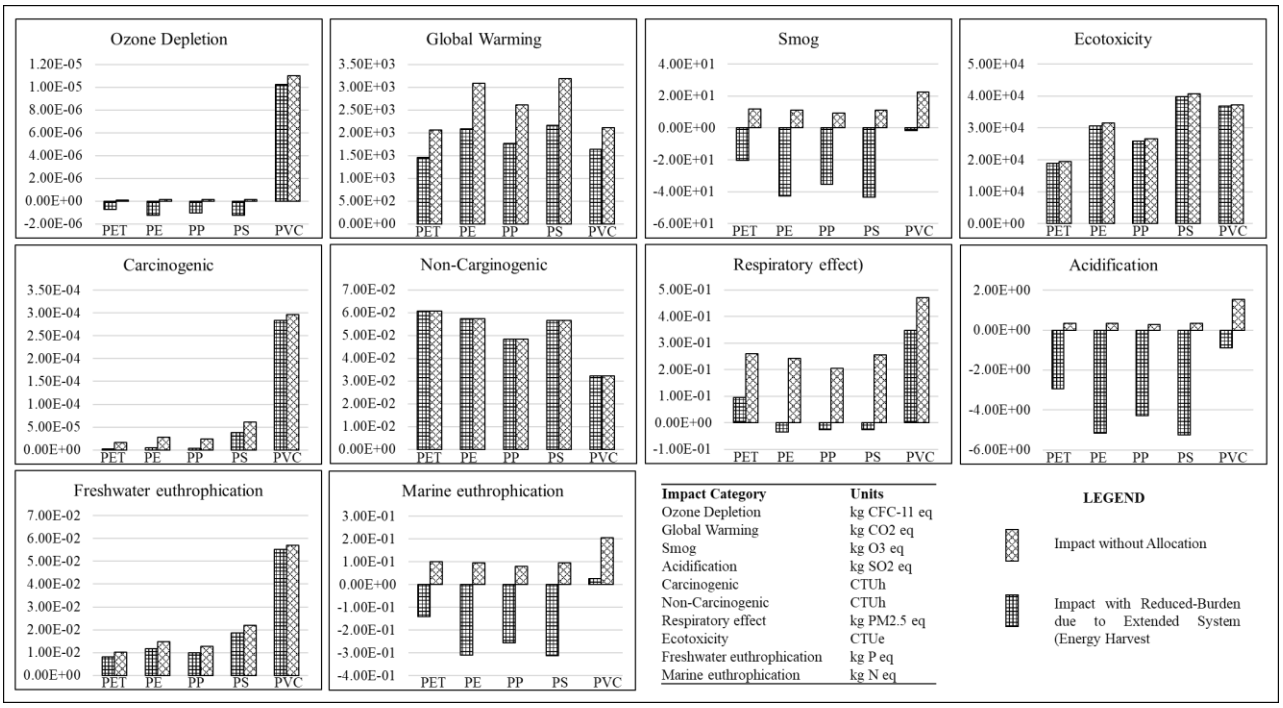

Figure 4: Environmental Impact of Incineration

The impacts of five types of plastic under two methods are presented in Figure 4. For ozone depletion, PVC shows a significantly higher impact because its high chlorine content and toxic nature require large quantities of chemicals during DeNOx treatment, desulfurization, and water treatment processes, which collectively increase ozone-depleting emissions. When the reduced-burden method is applied, the other plastics exhibit negative ozone-depletion values because the energy recovered from incineration displaces conventional fossil-fuel-based heat and electricity generation.

In terms of Global Warming Potential (GWP), PE and PS have higher contributions due to their greater carbon content, which leads to higher CO_2 emissions during combustion. The GWP of the system under the reduced-burden method is found to be higher than that of a natural-gas-based power plant producing the same amount of electricity. This occurs because plastics generally have

lower heating values than natural gas, and the incinerator releases small quantities of N_2O, a greenhouse gas with a very high GWP.

Overall smog formation from plastic incineration is relatively low. However, PVC exhibits a higher smog-forming potential due to the intensive use of inorganic chemicals during water treatment. When the benefits of energy recovery are considered, the overall smog impact becomes negative.

Ecotoxicity is primarily driven by residual waste and ash from the incineration process. Although these residues are treated with neutralizing agents, they still pose risks to organisms in both terrestrial and aquatic environments. Energy recovery has little influence on ecotoxicity because the reference energy system (e.g., natural-gas-based production) produces negligible solid residues that enter land or water.

As shown in Table 2, PVC emits significantly higher levels of toxic gases compared with the other plastics. Its carcinogenic impact is the highest, whereas PET shows the lowest carcinogenic potential. When energy recovery is taken into account, PET, PE, and PP show almost no carcinogenic impact, and PS has less than half the carcinogenic effect of PVC.

PET exhibits a comparatively higher non-carcinogenic impact due to the slightly greater use of V_2O_5, a catalyst used in the denitrification process. In contrast, PVC despite its high carcinogenic impact shows the lowest non-carcinogenic impact because it emits relatively lower amounts of NO_x, thereby reducing the contribution from the DeNOx process.

PVC also has a strong influence on respiratory effects, acidification, freshwater eutrophication, and marine eutrophication. These impacts are largely driven by the high consumption of quicklime during HCl neutralization and the substantial water demand for decarbonization.

5. Conclusion

As the use of plastic products continues to rise rapidly, managing plastic waste requires substantial effort. For several decades, plastic waste has been incinerated; however, the specific impacts of burning individual plastic types on human health and ecosystems have not been extensively studied. This study evaluates the impacts of incinerating five major plastic types independently. In conventional incineration systems, all waste is fed together without segregation, preventing researchers from identifying material-specific impacts and limiting available information to only the cumulative burden of the entire incinerator. This study demonstrates how the environmental impacts of incineration differ significantly among the five major plastic types, challenging the common assumption that all plastics behave similarly during combustion. Because a universal weighting system for environmental impact categories does not exist, the relative importance of each impact remains context-dependent and may vary across regions and nations. Despite this, the study successfully identifies material-specific impacts and shows how the overall environmental burden changes when energy recovery in the form of heat and electricity is included. Notably, PVC exhibits severe human-health-related impacts and should be excluded from incineration, with alternative treatment methods such as mechanical or chemical recycling considered instead. In contrast, PET, PE, PP, and PS demonstrate comparatively lower impacts in categories such as ozone depletion, smog formation, acidification, respiratory effects, and marine eutrophication, indicating their potential suitability for energy recovery applications. However, certain impact

categories including global warming, ecotoxicity, non-carcinogenic effects, and freshwater eutrophication remain elevated due to pollution-control processes, highlighting unavoidable trade-offs in incineration-based waste management.

Overall, the findings provide valuable guidance for stakeholders, policymakers, and local authorities by clarifying which plastics are more appropriate for incineration and which pose unacceptable risks. By identifying plastic types associated with severe or "red-listed" impacts, decision-makers can selectively exclude problematic materials from incineration systems and avoid disproportionate environmental or health burdens. These insights support the development of more effective, material-specific plastic waste management strategies and contribute to more informed, sustainable decisions regarding energy recovery and waste treatment infrastructure.

Future Works

Future research will focus on quantifying microplastic emissions from incineration, conducting a life cycle cost analysis, and evaluating the associated socio-economic impacts.

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Data Availability

All datasets are available from the author and will be provided upon reasonable request.

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