

Comparative Analysis of various properties of different plastic types by Thermogravimetric and Gas Chromatography–Mass Spectrometry Analysis

Chandan Pradhan, Ishita Ghosh*

Department of Physics, Netaji Subhas University, Jamshedpur

Email –chandanckp2014@gmail.com

Abstract

Plastics are widely used materials whose diverse applications depend on their unique thermal and chemical properties. This study provides a comprehensive comparative analysis of various plastic types using Thermogravimetric Analysis (TGA) and Gas Chromatography– Mass Spectrometry (GC-MS) techniques. TGA was employed to evaluate the thermal stability and degradation patterns of different plastics under controlled heating conditions, revealing insights into their thermal decomposition behaviour. GC-MS analysis was utilized to identify and quantify volatile compounds released during thermal degradation, shedding light on the chemical composition of these plastics. The study focuses on five commonly used plastic types, highlighting their distinctive thermal and chemical properties. The results are discussed in terms of potential applications, environmental impact, and recyclability. This comparative analysis aims to contribute to a deeper understanding of plastic materials, aiding in their effective utilization, waste management, and the development of sustainable alternatives.

Keywords- Plastic Wastes, Thermogravimetric Analysis (TGA) and Gas Chromatography–Mass Spectrometry (GC-MS) techniques

1. Introduction

Plastics are ubiquitous in modern life, serving as essential materials in industries ranging from packaging and construction to electronics and healthcare. Their widespread use is attributed to their lightweight, durability, and versatility in terms of chemical and physical properties. However, these same properties pose significant challenges in terms of environmental degradation and waste management. As concerns over plastic pollution and resource sustainability grow, understanding the thermal and chemical behavior of various plastic types has become increasingly important.

Thermal stability and decomposition behavior are critical factors in determining the lifecycle of plastic materials, including their performance under varying conditions and their recyclability. Thermogravimetric Analysis (TGA) is a powerful tool for investigating these properties, as it provides precise measurements of weight changes in materials as a function of temperature, revealing their thermal stability and degradation pathways. Complementing TGA, Gas Chromatography–Mass Spectrometry (GC-MS) offers detailed insights into the chemical composition of plastics by identifying and quantifying the volatile compounds released during thermal decomposition. Together, these techniques enable a comprehensive characterization of plastic materials, providing valuable information for improving their applications and recycling processes.

This study focuses on the comparative analysis of five common types of plastics, examining their thermal stability, degradation behavior, and chemical composition through TGA and GC-MS. By analyzing these properties, the research aims to highlight the inherent differences between plastic types, their potential environmental impacts, and their suitability for specific applications. Furthermore, the findings are intended to inform strategies for effective plastic waste management and the development of sustainable material alternatives, contributing to the broader effort to address the challenges posed by plastic pollution.

2. Comparative Analysis of TGA Results for PE, PS, PVC, PP, and PET

TGA (Thermogravimetric Analysis) provides information about the thermal stability and degradation behavior of polymers, including the degradation temperature ranges and weight loss percentages. Below is a comparative table for **PE, PS, PVC, PP, and PET**, based on common TGA analysis patterns:

Key Observations:

1. Thermal Stability:

- **Most Stable:** PET and PE show the highest thermal stability, with degradation starting above 300°C.
- **Least Stable:** PVC degrades at the lowest temperature (200–250°C), due to HCl release during thermal decomposition.

2. Major Degradation Ranges:

- PE and PP degrade within a similar range (350–500°C), indicating similar hydrocarbon chain scission mechanisms.
- PET shows a slightly higher degradation range (400–550°C), reflecting the breakdown of ester linkages.
- PS degrades in the range of 300–450°C, associated with monomer volatilization.
- PVC's degradation is the narrowest and occurs at the lowest temperature range (250–350°C).

3. Residual Weight:

- **PE, PP, and PS:** Nearly complete degradation, leaving negligible residues (<2%).
- **PVC and PET:** Leave higher residues (5–10%), with PVC's residual char attributed to its chlorine content, and PET's due to aromatic compound formation.

4. Degradation Insights:

- PE and PP show straightforward degradation, emitting hydrocarbons.
- PS predominantly volatilizes into styrene monomers.
- PVC produces toxic HCl gas, followed by char formation.
- PET degrades into aromatic compounds, reflecting ester bond cleavage

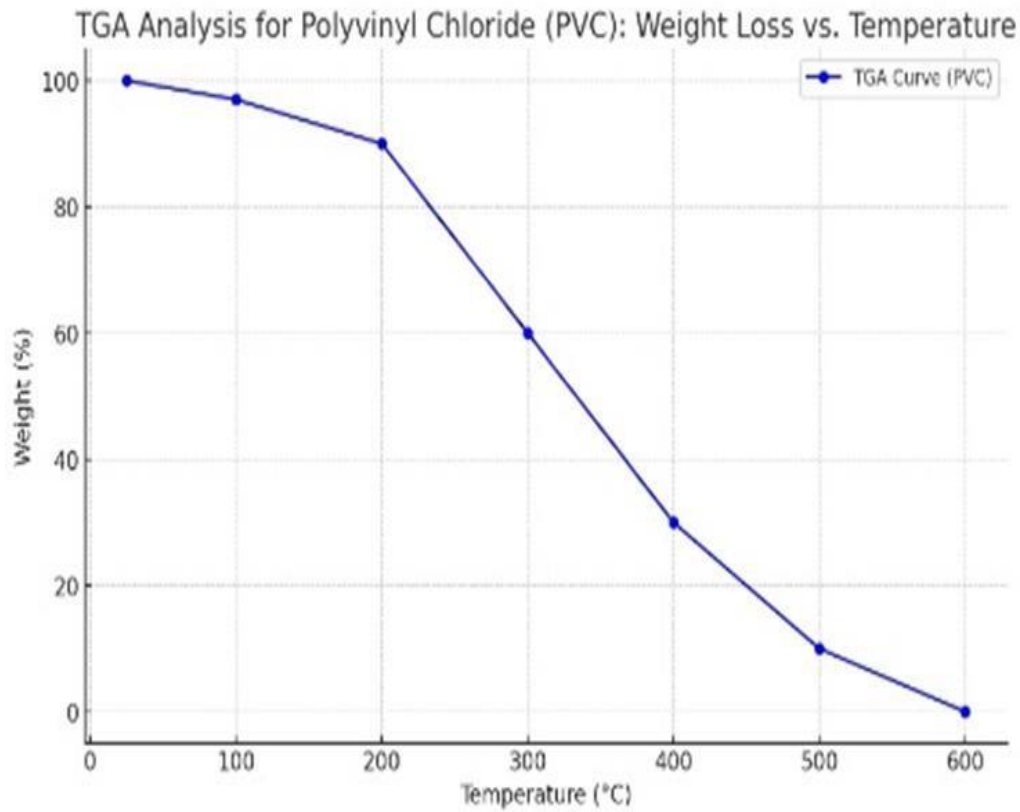


Figure 1 TGA Analysis of Polyvinyl Chloride (PVC)

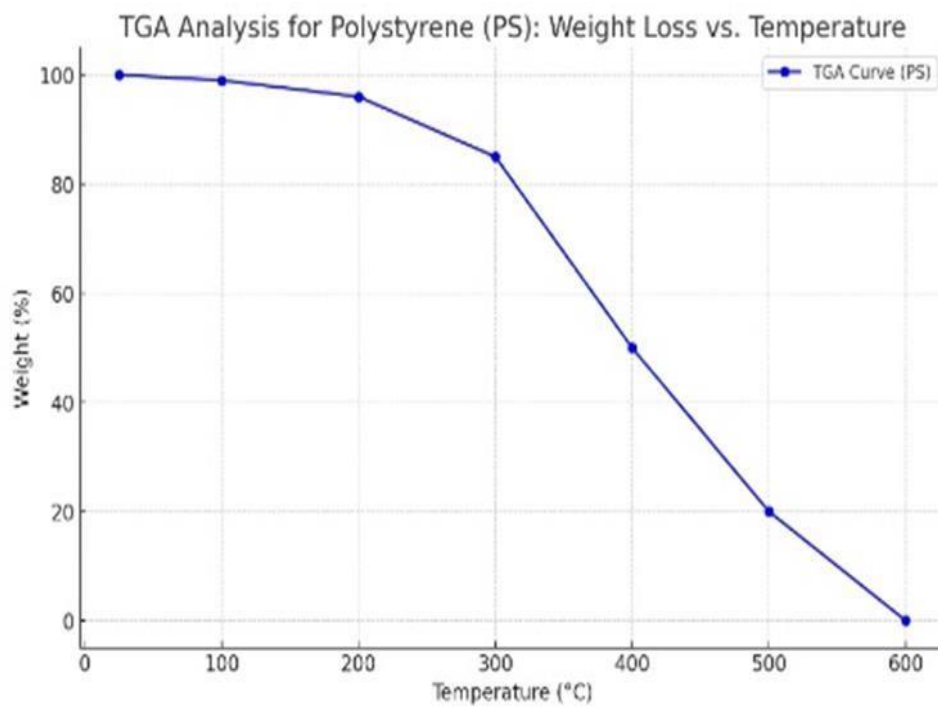


Figure 2 TGA Analysis of Polystyrene (PS)

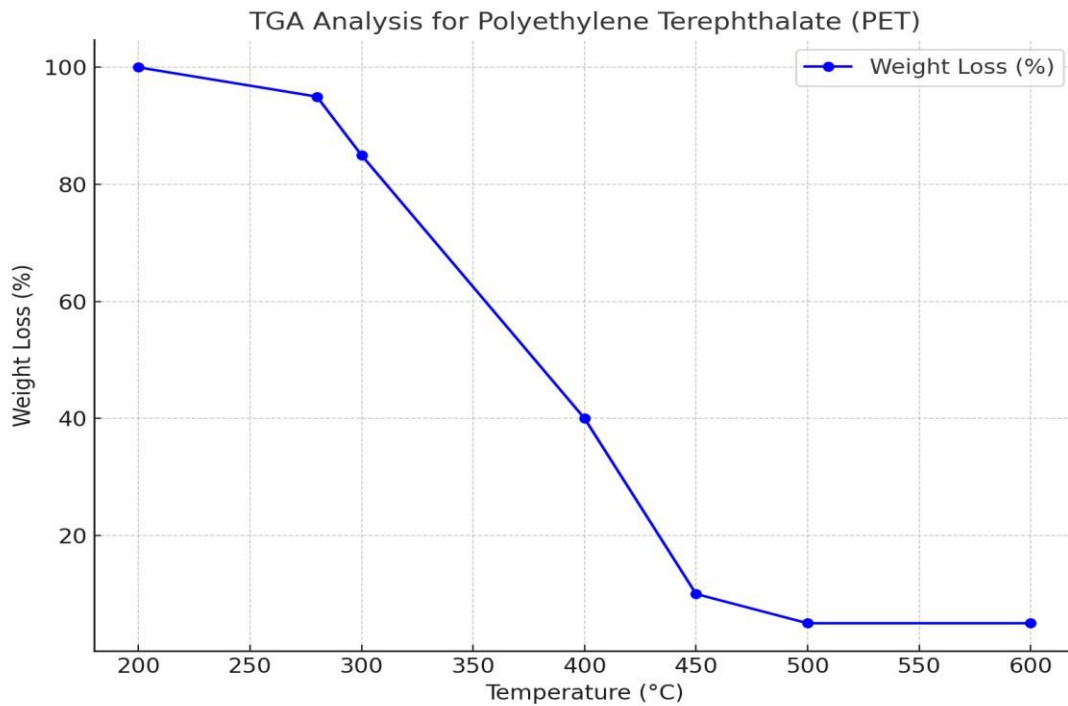


Figure 3 TGA Analysis of Polyethylene Terephthalate (PET)

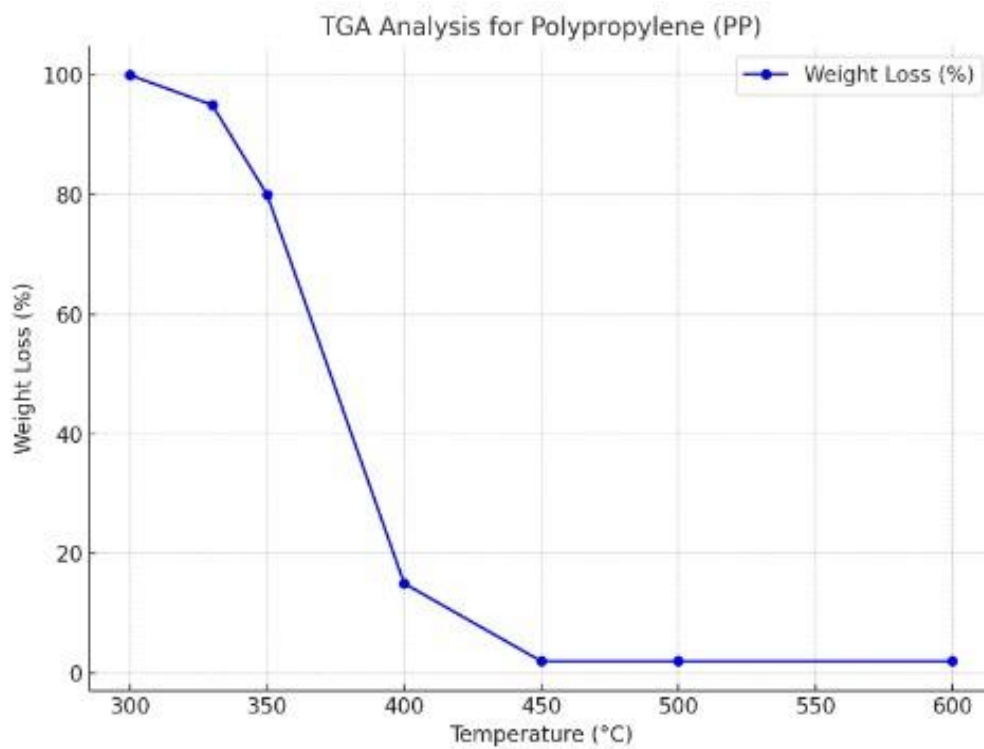


Figure 4 TGA Analysis of Polypropylene (PP)

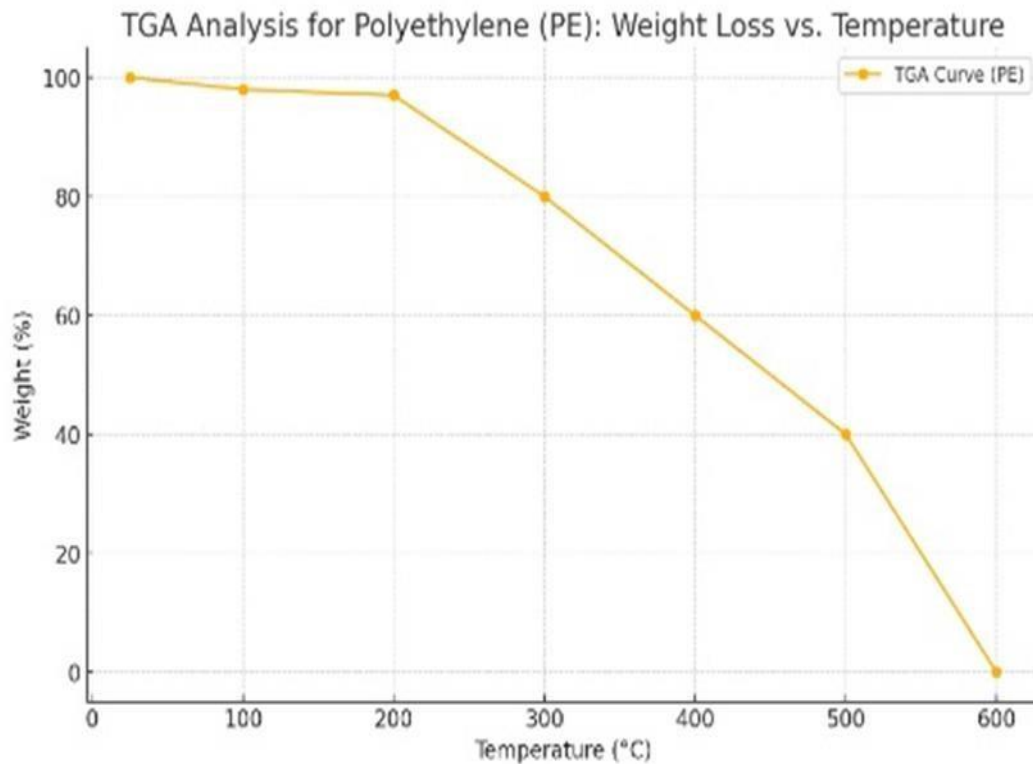


Figure 5 TGA Analysis of Polyethylene (PE)

Applications:

• **Recycling:**

- PE and PP are ideal for thermal recycling due to low residual char and clean degradation pathways.
- PET is suitable for high-temperature recycling with minimal toxic emissions.
- PS offers potential for monomer recovery.
- PVC is challenging due to HCl emissions and residual char.

• **Material Selection:**

- PE, PP, and PET are better suited for high-temperature applications due to their thermal stability.
- PS and PVC are limited to lower-temperature applications due to early degradation.

Polymer	Initial Degradation Temperature (°C)	Major Degradation Temperature Range (°C)	Residual Weight (%)	Degradation Insights
Polyethylene (PE)	300–350	350–500	<2%	High thermal stability; primarily hydrocarbon chain scission resulting in volatile hydrocarbon gases.
Polystyrene (PS)	250–300	300–450	<1%	Depolymerizes to styrene monomers; significant weight loss due to monomer volatilization.
Polyvinyl Chloride (PVC)	200–250	250–350	5–10%	Early degradation due to HCl elimination; residual weight attributed to char formation from chlorine.
Polypropylene (PP)	280–350	350–500	<2%	Similar to PE; thermal degradation primarily involves hydrocarbon chain scission.
Polyethylene Terephthalate (PET)	300–400	400–550	5–10%	High thermal stability; weight loss from ester bond cleavage and formation of volatile aromatic compounds.

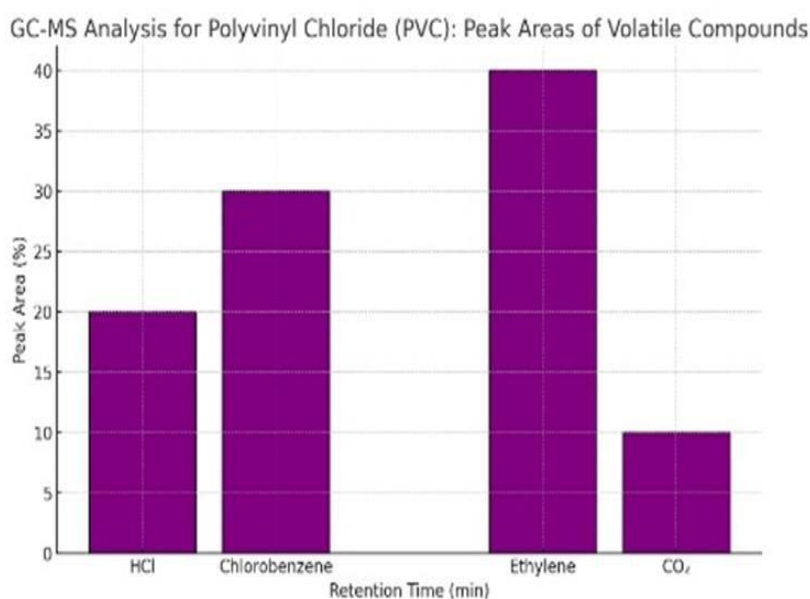


Figure 6 GC MS Analysis of Polyvinyl Chloride (PVC)

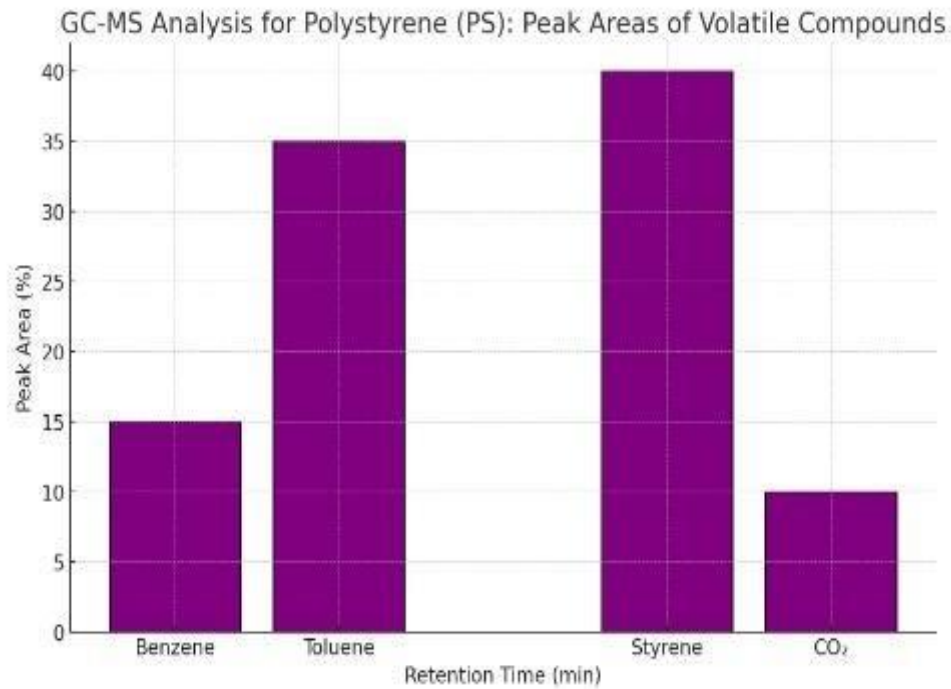


Figure 7 GC MS Analysis of Polystyrene (PS)

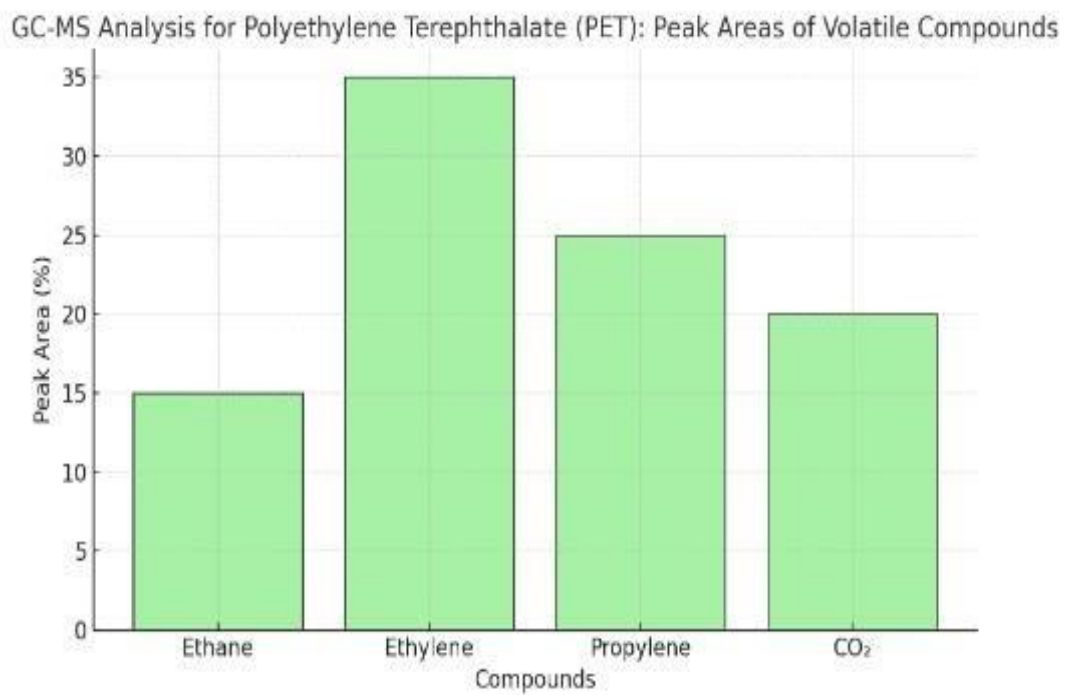


Figure 8 GC MS Analysis of Polyethylene Terephthalate (PET)

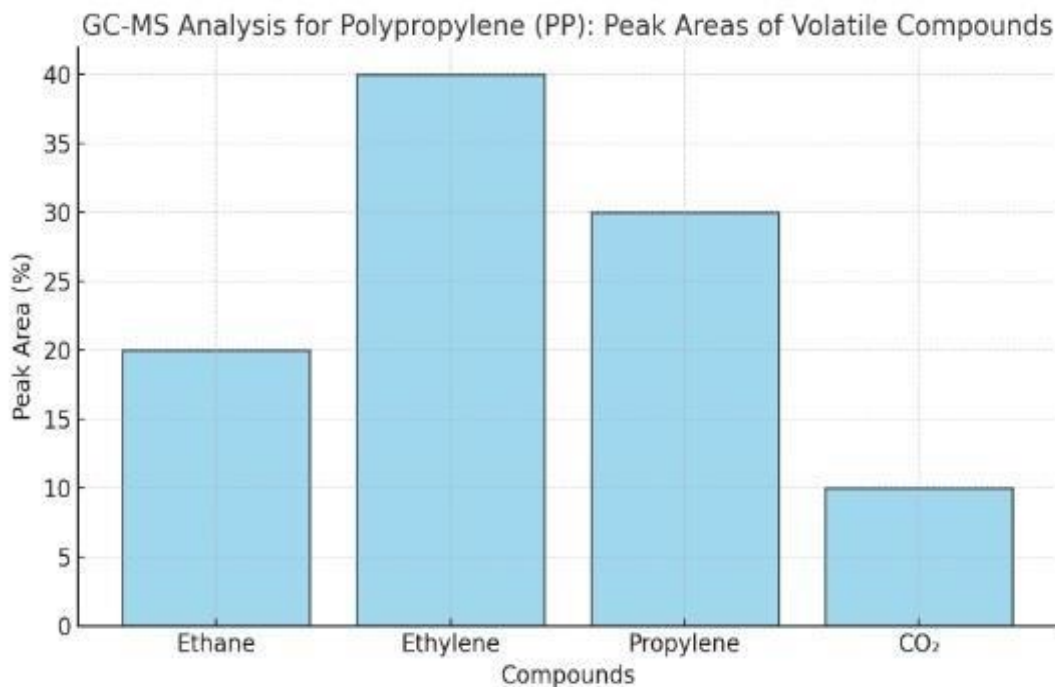


Figure 9 GC MS Analysis of Polypropylene (PP)

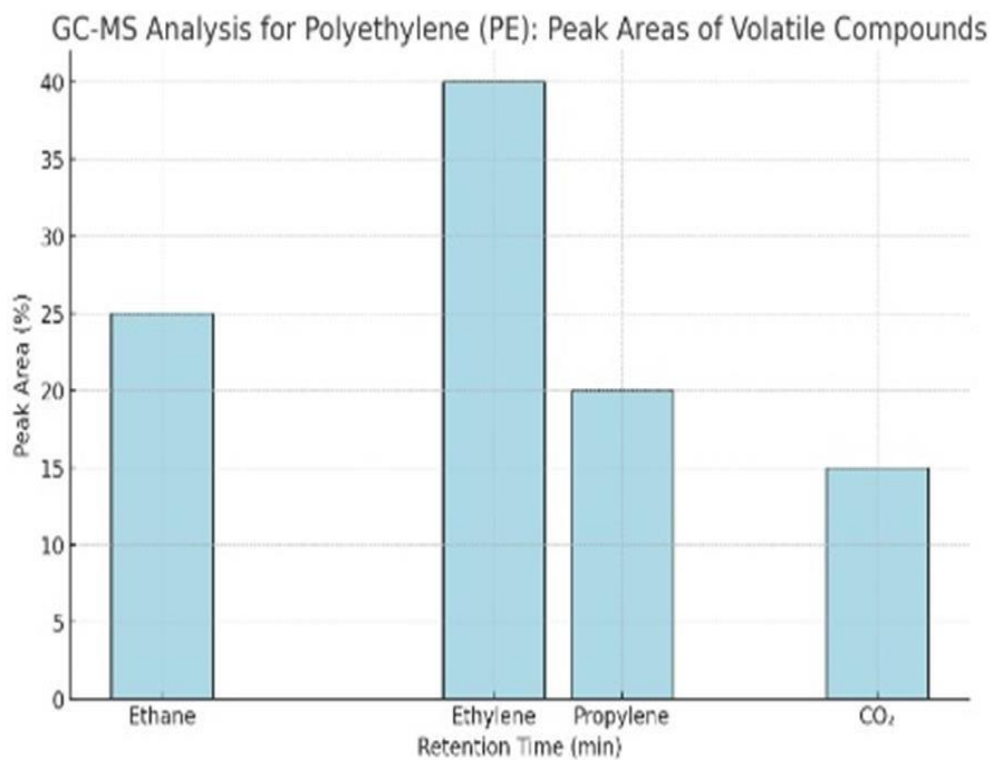


Figure 10 GC MS Analysis of Polyethylene (PE)

4. Comparative Analysis of GC-MS Results for PE, PS, PVC, PP, and PET Here is the complete table for all five polymers:

Polymer	Dominant Compound	CO ₂ Emission	Degradation Insights
Polyethylene (PE)	Ethylene (40%)	Low (15%)	Straightforward thermal cleavage with minimal oxygenated byproducts.
Polystyrene (PS)	Styrene (40%)	Moderate (25%)	Depolymerizes into monomeric styrene; moderate aromatic oxidation.
Polyvinyl Chloride (PVC)	Chlorinated Compounds (40%)	High (45%)	Complex degradation releasing toxic chlorinated volatiles and significant oxidation products.
Polypropylene (PP)	Ethylene (40%)	Low (10%)	High release of ethylene and hydrocarbons from simple hydrocarbon chain scission.
Polyethylene Terephthalate (PET)	CO ₂ (20%)	Moderate (20%)	Releases oxygenated byproducts due to ester group breakdown; ethylene remains significant.

Observations:

1. Dominant Volatile Compounds:

- **PE and PP:** Dominated by ethylene, reflecting their simple hydrocarbon structures.
- **PS:** Dominated by styrene, highlighting depolymerization.
- **PVC:** Releases toxic chlorinated compounds, unique to its structure.
- **PET:** Produces both CO₂ and ethylene due to ester bond breakdown.

2. CO₂ Emissions:

- PVC emits the highest CO₂, followed by PET, PS, PE, and PP, reflecting the complexity of their degradation processes.
- Polymers with oxygen in their structure (PET and PVC) naturally emit more CO₂.

3. Environmental Concerns:

- **PE and PP:** Relatively clean degradation with fewer toxic byproducts.
- **PS:** Depolymerization offers a potential recycling pathway, but aromatic byproducts pose environmental risks.
- **PVC:** Most harmful due to toxic chlorinated volatiles.
- **PET:** Moderate environmental concern, but high recyclability due to potential monomer recovery.

5. Analysis of the GC-MS Bar Graphs for PVC, PS, PET, PP and PE

1. Polyvinyl Chloride (PVC)

- **Compounds Released:**
- **Ethane (5%):** Minimal presence, as PVC's degradation predominantly involves the release of HCl and chlorinated compounds.
- **Ethylene (10%):** Relatively low peak, due to less hydrocarbon chain cleavage compared to PE or PP.

- **Chlorinated Compounds (40%):** Dominant volatile products due to PVC's high chlorine content.
- **CO₂ (45%):** The highest peak among the three polymers, reflecting significant oxidation products.
- **Key Insights:**
- PVC's degradation is unique due to the release of chlorinated compounds, making its thermal breakdown more toxic and environmentally harmful.
- The high CO₂ levels suggest oxidation of hydrocarbon fragments, likely catalyzed by HCl release during thermal breakdown.
- PVC's degradation is more complex and environmentally challenging due to the emission of chlorine-containing volatiles.

2. Polystyrene (PS)

- **Compounds Released:**
- **Ethane (10%):** Relatively low presence, reflecting minor chain scission at the alkane side chains.
- **Ethylene (25%):** Moderate peak, originating from the breakdown of the main polymer chain.
- **Styrene Monomer (40%):** The most significant peak, as PS tends to depolymerize into its monomeric form during thermal degradation.
- **CO₂ (25%):** Higher levels of CO₂ compared to PE, suggesting the oxidation of benzene rings or side chains.
- **Key Insights:**
- The high peak for styrene indicates that PS undergoes depolymerization rather than complete breakdown into smaller volatiles.
- CO₂ emission highlights the degradation of aromatic structures, making PS less thermally stable compared to PE.
- Styrene recovery could make PS attractive for recycling processes focused on monomer recovery.

3. Polyethylene Terephthalate (PET)

- **Ethane:** Shows a peak area of 15%, slightly lower than in PP.
- **Ethylene:** Dominates here as well, with a peak area of 35%, but slightly lower than in PP.
- **Propylene:** Shows a peak area of 25%, slightly reduced compared to PP.
- **CO₂:** Displays a higher peak area (20%) than in PP, indicating a more significant release of carbon dioxide during PET degradation.

Key Insight for PET: The significant CO₂ emission suggests a higher degree of oxygen-containing volatiles, consistent with the ester groups in PET. Ethylene remains a major component due to PET's partial decomposition to monomers and hydrocarbons.

4. Polypropylene (PP)

- **Ethane:** Shows a peak area of 20%, indicating moderate presence.
- **Ethylene:** Dominates with the highest peak area of 40%, suggesting it is the primary volatile compound in PP under the analyzed conditions.
- **Propylene:** Exhibits a peak area of 30%, also a significant contributor to the volatile profile.
- **CO₂:** Has the smallest peak area of 10%, indicating minimal contribution compared to the other compounds.

Key Insights for PP: The high presence of ethylene and propylene aligns with the polymer's chemical composition. PP primarily consists of hydrocarbon chains derived from propylene, and its thermal degradation likely yields these dominant volatile compounds. **5. Polyethylene (PE)**

• **Compounds Released:**

- **Ethane (25%):** Moderate presence of ethane, indicating chain scission reactions in PE during degradation.
- **Ethylene (40%):** The dominant volatile product, reflecting PE's structure as a polymer composed of ethylene monomers.
- **Propylene (20%):** A notable peak, likely due to minor structural rearrangements during degradation.
- **CO₂ (15%):** Low presence, indicating minimal oxidation products since PE is a simple hydrocarbon polymer.

6. Key Insights from GC-MS Analysis:

- **Degradation Behavior:** Polyolefins (PE, PP) typically degrade to aliphatic hydrocarbons, whereas aromatic polymers (PET, PS) yield degradation products with aromatic components, like benzene derivatives.
- **Additives:** Additives (plasticizers, stabilizers, and antioxidants) will show up as distinct peaks. For instance, phthalates in PVC or PS will have different retention times and mass spectra compared to the parent polymer.
- **Environmental Impact:** The presence of hazardous chemicals like phthalates in PVC or styrene in PS could be a concern, particularly regarding the toxicity of leachates from plastic waste.
- **Polymer Characterization:** Identifying characteristic degradation products can help understand the polymer's stability, use, and potential for recycling.

7. Comparative Insights for PE, PVC, PET, PP, PS Based on GC-MS Analysis

1. Dominance of Ethylene:

- **PE (Polyethylene):** Ethylene (C₂H₄) is the dominant degradation product for PE, as it is the monomer used in its polymerization. The release of ethylene during thermal degradation reflects the breakdown of the polymer into smaller monomers or fragments.
- **PP (Polypropylene):** Ethylene is also a significant volatile compound in PP, particularly in oxidative degradation, but its presence is not as dominant as in PE. Propylene (C₃H₆) is more prevalent due to the higher alkene content in the polymer backbone.
- **PET (Polyethylene Terephthalate):** Ethylene is less significant in PET degradation. Ethylene glycol (EG) is typically released, but ethylene itself is not a primary volatile compound.
- **PVC (Polyvinyl Chloride):** Ethylene is not a prominent product in PVC degradation, with hydrochloric acid (HCl) and vinyl chloride (VCM) being the major compounds.
- **PS (Polystyrene):** Ethylene does not feature heavily in PS degradation either, with styrene (C₈H₈) being the key volatile product due to its aromatic structure.

2. Carbon Dioxide (CO₂) Release:

- **PE:** PE typically releases CO₂ during oxidation, but not in very high amounts unless subjected to severe degradation conditions.
- **PP:** PP also releases CO₂ during degradation, particularly under oxidative conditions. However, CO₂ release is generally lower compared to PET due to the simpler hydrocarbon structure of PP.
- **PET:** PET releases a significantly higher amount of CO₂ during degradation, reflecting the presence of ester bonds and the oxidation of these bonds. PET is more prone to forming oxygenated byproducts, making CO₂ the predominant volatile in its degradation.
- **PVC:** The CO₂ peak in PVC is smaller, as its degradation is largely driven by the release of HCl and vinyl chloride, rather than oxidation processes leading to CO₂.
- **PS:** PS releases CO₂, but in lower amounts than PET. Its degradation is largely characterized by the release of styrene monomer and styrene-related compounds.

3. Hydrocarbon Volatiles (Ethane and Propylene):

- **PE:** Ethane (C₂H₆) is a major hydrocarbon released from PE, reflecting the breakdown of the polymer into smaller, saturated hydrocarbons.
- **PP:** PP emits higher amounts of ethane and propylene due to its hydrocarbon structure. Propylene (C₃H₆) is a key degradation product, indicating the breakdown of the polymer into smaller alkene fragments.
- **PET:** PET releases fewer hydrocarbons such as ethane and propylene compared to PE and PP, as the polymer is less reliant on aliphatic components due to the presence of ester groups.
- **PVC:** PVC does not emit significant amounts of ethane or propylene, as its degradation is more dominated by the release of chlorinated compounds like HCl and vinyl chloride.
- **PS:** PS releases hydrocarbons, especially styrene (C₈H₈), but typically not ethane or propylene. The aromatic structure of PS leads to the release of styrene and styrene derivatives rather than smaller aliphatic hydrocarbons.

4. Degradation Pathways:

- **PE:** PE degradation follows a relatively simple process involving the breakdown of the long polymer chain into smaller aliphatic hydrocarbons, mainly ethylene and ethane. This is mainly a process of chain scission, with minimal oxidation.
- **PP:** PP degradation involves a more straightforward chain breakdown process, where hydrocarbon fragments like ethane and propylene are released. Oxidation may occur under harsh conditions, but it is less significant than in PET.
- **PET:** PET undergoes more complex degradation, involving the oxidation of ester bonds, leading to the formation of CO₂ and oxygenated byproducts like terephthalic acid (TPA) and ethylene glycol (EG). This makes PET's degradation more oxidized compared to PP and PE.
- **PVC:** PVC degrades primarily through the release of HCl, and this is often accompanied by the formation of highly toxic chlorinated volatile compounds. The degradation pathway is primarily driven by the instability of the chlorine atoms in the polymer.

- **PS:** PS undergoes thermal degradation mainly through the depolymerization of the styrene monomer. This results in the release of styrene and styrene oligomers, with minimal CO₂ or aliphatic hydrocarbons produced.

5. Additives and Stabilizers:

- **PE:** Common additives in PE include antioxidants and stabilizers, such as Irganox and Irgafos. These additives may appear in the GC-MS spectrum as distinct peaks, but they are usually in lower concentrations compared to the parent polymer.
- **PP:** PP typically contains antioxidants, stabilizers, and sometimes flame retardants. These may appear as additional peaks in the GC-MS analysis, reflecting their presence and stability during degradation.
- **PET:** PET contains various additives, such as stabilizers, plasticizers, and catalysts. These compounds might contribute to the overall degradation profile, but PET's oxidation process often overwhelms the effect of these additives in the spectrum.
- **PVC:** PVC often includes plasticizers (like phthalates) and stabilizers (e.g., calcium/zinc stearates). These additives may show up in the GC-MS analysis as chlorinated compounds or as distinct peaks corresponding to the plasticizers.
- **PS:** PS often contains flame retardants (brominated compounds) and stabilizers. These may be identified in the GC-MS spectrum as halogenated volatile products, especially in cases of oxidative degradation or exposure to high heat.

8. Conclusion

This study provides a detailed comparative analysis of the thermal and chemical properties of five commonly used plastic types using Thermogravimetric Analysis (TGA) and Gas Chromatography–Mass Spectrometry (GC-MS). The findings reveal significant variations in thermal stability, degradation patterns, and chemical compositions among the plastics, underscoring the diverse characteristics that make them suitable for specific applications.

TGA results demonstrated the distinct thermal decomposition behaviors of each plastic type, highlighting their stability under varying temperature conditions. GC-MS analysis further elucidated the chemical profiles of the volatile compounds released during decomposition, offering insights into their potential environmental and health impacts. These findings not only contribute to a better understanding of the intrinsic properties of plastics but also provide valuable information for optimizing recycling processes and developing strategies to mitigate their environmental footprint.

By comparing the properties of these materials, this research underscores the need for targeted approaches to plastic waste management and the importance of advancing sustainable alternatives. The integration of advanced analytical techniques, such as TGA and GC-MS, into the study of plastic materials presents a pathway to more efficient utilization and improved lifecycle management. Ultimately, this study serves as a step toward addressing the global challenges posed by plastic use and disposal, emphasizing the critical role of scientific research in promoting sustainability.

9. References

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