

How environmentally friendly is the disposal of clear aligners? A gas chromatography-mass spectrometry study

Elbe Peter,^a J. Monisha,^b V. P. Sylas,^c and Suja Ani George^d

Thrissur, Ernakulam, and Kottayam, Kerala, India

Introduction: Used clear aligner trays are often indiscriminately disposed of with general plastic waste and incinerated. This study aimed to analyze the smoke composition from incinerating 2 common aligner materials: glycol-modified polyethylene terephthalate (PET-G) and polyurethane. **Methods:** Each of the 2 materials in triplicate was thermoformed. The thermoformed trays were shredded and subjected individually to open-fire combustion, ignited using a methane torch, in a specially designed combustion chamber. The resultant smoke was collected and analyzed using gas chromatography-mass spectrometry to study its in-depth composition. **Results:** A total of 20 peaks, corresponding to 20 compounds, were identified from each of the 2 material samples. O-xylene (21.06%) showed the maximum concentration in the PET-G sample, whereas 1,4-dimethyl-1,3-cyclohexadiene in polyurethane (18.88%). The first peak in the PET-G sample corresponded to benzene with a relative concentration of 5.18%. Four compounds were common to both samples: 1,4-dimethyl-1,3-cyclohexadiene; 1,3-cyclohexadiene, 2,3-dimethyl-; 1-hydroxymethyl-4-methylenecyclohexane; and cyclohexanemethanol, 4-methylene-. **Conclusions:** Benzene, a group 1 carcinogen, was identified in the PET-G smoke sample, whereas tetrahydrofuran, a suspected carcinogen, was found in the polyurethane sample. Some compounds were hazardous, whereas most were skin, eye, and respiratory irritants. Possible mitigation strategies include proper case selection, efficient manufacturing, direct 3-dimensional printing, and developing biodegradable materials. Clinicians can set up 'used aligner collection points' to ensure responsible disposal. Proper disposal guidelines and stringent regulations are the need of the hour. (Am J Orthod Dentofacial Orthop 2025;167:39-46)

^aDepartment of Orthodontics and Dentofacial Orthopedics, Government Dental College, Thrissur, Kerala, India.

^bDepartment of Orthodontics and Dentofacial Orthopedics, St. Gregorios Dental College, Ernakulam, Kerala, India.

^cSchool of Environmental Sciences, Mahatma Gandhi University, Kottayam, Kerala, India.

^dDepartment of Orthodontics and Dentofacial Orthopedics, Government Dental College, Kottayam, Kerala, India.

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The study was conducted in the Department of Orthodontics and Dentofacial Orthopedics, Government Dental College, and the School of Environmental Sciences, Mahatma Gandhi University, Kerala, India. The research protocol was approved by the Institutional Review Board (IEC/M/22/2021/DCK).

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Address correspondence to: Elbe Peter, Department of Orthodontics and Dentofacial Orthopedics, Government Dental College, Thrissur, Kerala 680596, India; e-mail, elbeortho@yahoo.co.in.

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The demand for more esthetically pleasing and cozy appliances has grown dramatically over the recent years. Clear orthodontic appliances have been in use since the mid-1900s, but it was not until 1997 that Align Technology (Santa Clara, Calif) integrated contemporary technologies to offer clear aligner treatment (CAT) under the brand Invisalign. Currently, a diverse array of aligner manufacturers operates globally.

CAT employs a series of computer-generated customized trays to gradually guide teeth to predetermined positions. Thermoplastic polymers are employed in the fabrication of aligners, with glycol-modified polyethylene terephthalate (PET-G) being commonly used by most manufacturers.¹ In contrast, Invisalign uses a highly elastic thermoplastic polyurethane termed SmartTrack.²

The total number of aligner trays required per case varies widely based on the specific malocclusion being

addressed, with each tray replaced every ≤ 2 weeks. Although there is ample information available about their usage, there is limited guidance on their disposal.³ The disposal of used aligner trays poses a challenge as they constitute contaminated medical waste.⁴ However, there is a lack of established protocols for their proper handling,³ often resulting in their indiscriminate disposal alongside regular household waste. Incineration is one of the most common ways of general plastic waste disposal, others being recycling and deposition in landfills.⁵ Nevertheless, incineration of plastics is reported to release toxic fumes into the atmosphere, posing significant environmental and health hazards.⁶

Despite the growing body of research on CAT, their environmental impact remains unexplored. Hence, this study attempted to determine the combustion products generated during incineration of 2 distinct thermoplastic materials commonly used in clear aligner (CA) fabrication.

MATERIAL AND METHODS

The study was designed to investigate the environmental impact caused by 2 chemically different CA materials during incineration. It was conducted in the Department of Orthodontics and Dentofacial Orthopedics, Government Dental College, and the School of Environmental Sciences, Mahatma Gandhi University, Kerala, India. The research protocol was approved by the institutional review board (IEC/M/22/2021/DCK). The rationale of the study has been previously published.⁷

Sample collection

Thermoplastic CA sheets from 2 manufacturers, namely, Duran (Scheu-Dental GmbH, Iserlohn, Germany) and Zendura (Bay Materials LLC, Fremont, Calif), were procured, and a total of 3 sheets from each served as the investigative material. The former is PET-G-based, and the latter is polyurethane-based. These preformed sheets were thermoformed in a sample patient model using the Biostar vacuum-forming machine (SCHEU-DENTAL GmbH, Iserlohn, Germany).

The methodology described by Simoneit et al⁸ was adopted in this study. Each of the trays was shredded and subjected individually to low-temperature, open-fire combustion in a specially designed combustion chamber. The shredded plastic samples of known weight were spread out over a pre-cleaned stainless-steel tray and ignited with a methane torch. It was allowed to burn till the fire died out to produce the smoke. The smoke thus generated was collected using a high-

volume air sampler on a quartz fiber filter that was cleaned and weighed beforehand. The filters were desiccator-dried to a fixed weight, the collection area was gauged, and gravimetric analysis was used to calculate the mass of the particles.

Gas chromatography-mass spectrometry

Each sample was subjected separately to the gas chromatography-mass spectrometry (GC-MS) analyses on a Thermo Trace 1300 Gas Chromatograph (Thermo Scientific, Milan, Italy) coupled to a G2QToF Mass Analyzer for nontargeted analysis. The GC was operated under the following conditions: initially, at 50°C for 2 minutes, followed by a gradual increase to 300°C at a rate of 6°C per minute, and was held at 300°C for 20 minutes. Helium gas served as the carrier. The mass spectrometer functioned at 70 electron-volt, scanning from 50 to 650 daltons.

RESULTS

The detailed chemical composition of the smoke released after the incineration of PET-G and polyurethane aligner material is presented in [Tables I](#) and [II](#), respectively. The retention time of each compound, along with their peak area percentage in the chromatogram, are also provided ([Tables I](#) and [II](#)). A total of 20 distinct compounds were identified after the GC-MS analysis of the smoke samples of both PET-G and polyurethane. The GC-MS chromatograms of the PET-G and polyurethane samples are depicted in [Figures 1](#) and [2](#), respectively.

The area percentage reflects the relative concentration of each compound in a mixture. Analysis of the PET-G sample revealed that *o*-xylene had the highest concentration, accounting for 21.06% of the total, followed by octa-2,4,6-triene at 20.63% and 1,4-bis(methylene)cyclohexane at 13.69% ([Figs 1](#) and [3](#)). The first peak, with the shortest retention time of 2.099 minutes, corresponded to benzene, having a relative percentage of 5.18% ([Fig 4](#)). The last peak was identified as 2-Methyltricyclo(2.2.1.0 [2,6])heptane, with a retention time of 18.746 minutes and an area percentage of 1.34%.

In the case of polyurethane, the most abundant compound was 1,4-dimethyl-1,3-cyclohexadiene (18.88%), followed by 1-octanol (9.30%) and 2-pentene,2,4,4-trimethyl- (9.10%) ([Figs 1](#) and [5](#)). Tetrahydrofuran was the first compound to peak, with 1.910 minutes of retention time and 8.13 area percentage, whereas the last peak corresponded to 1,2-benzenedicarboxylic acid, bis(2-methylpropyl) ester (retention time = 18.676 minutes; area = 3.66%).

Table I. GC-MS chromatogram compounds list of PET-G

Peak No.	Retention time	Compound name	Compound formula	Molecular weight	Area (%)
1	2.099	benzene	C ₆ H ₆	78	5.18
2	3.130	toluene	C ₆ H ₅ CH ₃	92	4.22
3	3.664	1-methylcycloheptene	C ₈ H ₁₄	110	1.03
4	3.781	1,4-bis(methylene)cyclohexane	C ₈ H ₁₂	108	13.69
5	3.842	2,5,5-trimethylcyclopentadiene	C ₈ H ₁₂	108	1.78
6	4.176	(E,E,E)-2,4,6-octatriene	C ₈ H ₁₂	108	1.04
7	4.389	octa-2,4,6-triene	C ₈ H ₁₂	108	20.63
8	4.537	2,3-dimethyl-cyclohexa-1,3-diene	C ₈ H ₁₂	108	6.66
9	4.707	o-xylene	C ₈ H ₁₀	106	21.06
10	4.742	cyclopentene, 1-ethenyl-3-methylene-	C ₈ H ₁₀	106	3.31
11	5.114	1,4-dimethyl-1,3-cyclohexadiene	C ₈ H ₁₂	108	3.66
12	7.163	6-methyl-3-cyclohexenecarboxaldehyde	C ₈ H ₁₂ O	124	1.64
13	7.576	1-cyclohexene-4-carboxaldehyde, 1-methyl	C ₈ H ₁₂ O	124	1.27
14	8.422	1-hydroxymethyl-4-methylenecyclohexane	C ₈ H ₁₄ O	126	2.22
15	8.778	cyclohexanemethanol, 4-methylene-	C ₈ H ₁₄ O	126	2.71
16	9.162	benzoylformic acid	C ₈ H ₆ O ₃	150	2.57
17	9.444	benzoic acid	C ₇ H ₆ O ₂	122	3.20
18	15.077	2-Imidazolidinone, 4-ethyl-4-phenyl-	C ₁₁ H ₁₄ N ₂ O	190	1.42
19	18.357	Tricyclo[2.2.2.0 (1,4)]octane	C ₈ H ₁₂	108	1.37
20	18.746	2-methyltricyclo[2.2.1.0 (2,6)]heptane	C ₈ H ₁₂	108	1.34

Table II. GC-MS chromatogram compounds list of polyurethane

Peak No.	Retention time	Compound name	Compound formula	Molecular weight	Area (%)
1	1.910	tetrahydrofuran	C ₄ H ₈ O	72	8.13
2	3.312	1,4-hexadiene, 2,3-dimethyl-	C ₆ H ₁₄	110	4.04
3	3.458	3-pentanone, 2,4-dimethyl-	C ₇ H ₁₄ O	114	3.43
4	3.780	cyclohexane, 1,4-bis(methylene)-	C ₈ H ₁₂	108	6.75
5	4.388	cyclohexane, 1,4-bis(methylene)-	C ₈ H ₁₂	108	4.69
6	4.499	1,4-dimethyl-1,3-cyclohexadiene	C ₈ H ₁₂	108	18.88
7	4.535	1,3-cyclohexadiene, 2,3-dimethyl-	C ₈ H ₁₂	108	2.92
8	4.636	2,4-hexadiene, 2,5-dimethyl-	C ₈ H ₁₄	110	2.43
9	4.705	benzene, 1,3-dimethyl-	C ₈ H ₁₀	106	3.83
10	5.069	2-pentene, 2,4,4-trimethyl-	C ₈ H ₁₆	112	9.10
11	5.989	1,4-butanediol	C ₄ H ₁₀ O ₂	90	1.63
12	6.581	cyclotetrasiloxane, octamethyl-	C ₈ H ₂₄ O ₄	296	1.37
13	8.093	1-octanol	C ₈ H ₁₈ O	130	9.30
14	8.422	1-hydroxymethyl-4-methylenecyclohexane	C ₈ H ₁₄ O	126	2.45
15	8.779	cyclohexanemethanol, 4-methylene-	C ₈ H ₁₄ O	126	2.19
16	9.126	cyclotetrasiloxane, octamethyl-	C ₈ H ₂₄ O ₄ Si ₄	296	3.71
17	13.778	butylated hydroxytoluene	C ₁₅ H ₂₄ O	220	6.75
18	13.854	trisiloxane, 1,1,1,5,5,5-hexamethyl-3,3-bis[[trimethylsilyl]oxy]-	C ₁₂ H ₃₆ O ₄ Si ₅	384	2.87
19	14.362	butylated hydroxytoluene	C ₁₅ H ₂₄ O	220	1.86
20	18.676	1,2-benzenedicarboxylic acid, bis(2-methylpropyl) ester	C ₁₆ H ₂₂ O ₄	278	3.66

The compounds 1,4-dimethyl-1,3-cyclohexadiene; 1,3-cyclohexadiene, 2,3-dimethyl-; 1-hydroxymethyl-4-methylenecyclohexane; and cyclohexanemethanol, 4-methylene- were common to both samples, but at different concentrations (Tables I and II).

DISCUSSION

The advent of CAs represents a profound breakthrough in orthodontics, providing an edge over conventional fixed

appliances in terms of improved esthetics and patient compliance.⁹ Advancements in digital technology have facilitated the precise design and manufacture of aligners, ensuring accurate fit and predictable tooth movements.¹⁰ The mean accuracy of Invisalign has increased significantly from 41% in 2008 to 50% in 2020.^{11,12} In addition, the psychosocial benefits associated with their discrete nature have enhanced overall patient satisfaction, contributing to improved quality of life.^{13,14}

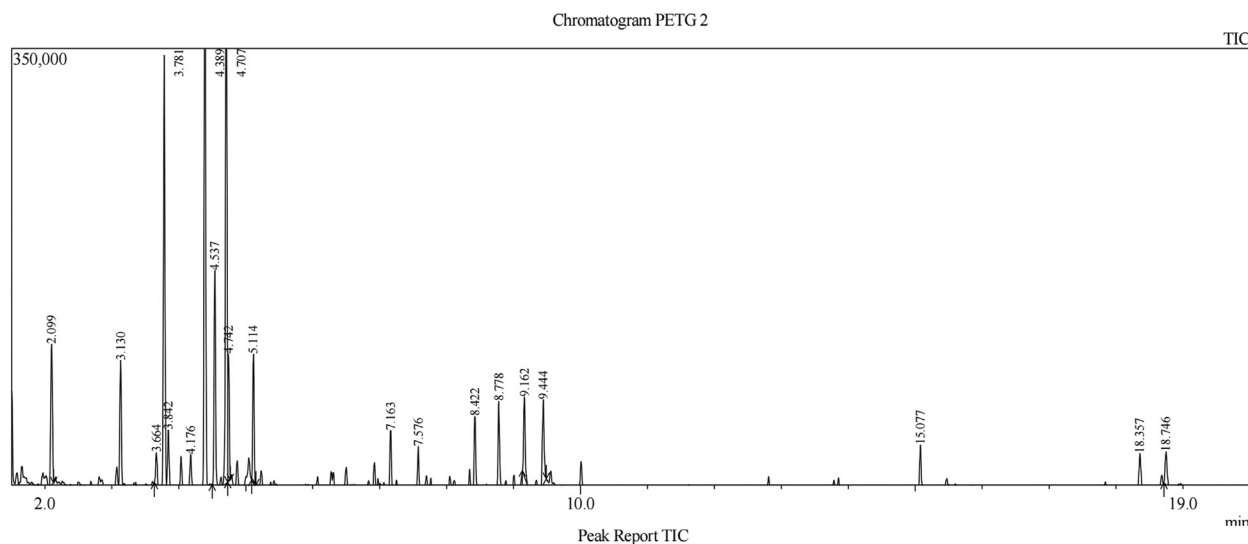


Fig 1. GC-MS chromatogram of PET-G sample.

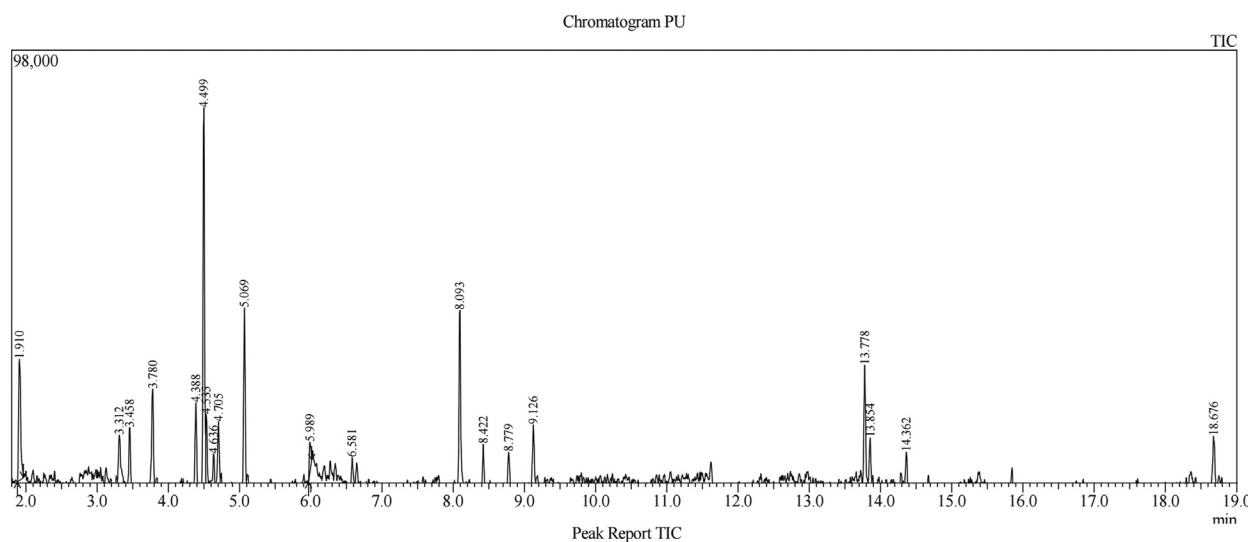
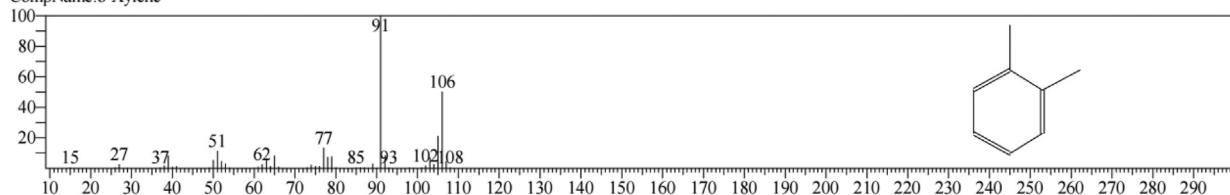


Fig 2. GC-MS chromatogram of polyurethane sample.

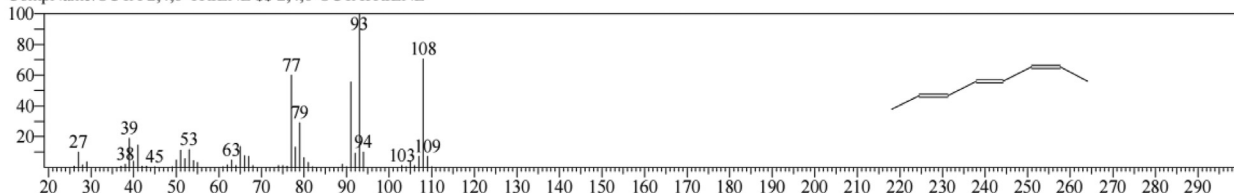
A diverse array of thermoplastic polymers, including but not limited to polyurethane, polypropylene, PET-G, and polyester, are employed in the manufacture of aligners.¹⁵ Nonetheless, the precise molecular composition remains an intriguing trade secret.¹⁶ Invisalign (Align Technology, Inc., Santa Clara, Calif) currently employs SmartTrack LD30 (Align Technology, Inc., San Jose, Calif), which is a highly specialized multi-layer aromatic thermoplastic polyurethane engineered for superior performance.² A newer addition is the direct 3-dimensional (3D) printed aligners, in which, again, the exact composition is obscure.¹⁶

The number of aligner trays per case is contingent on the severity of the problem and the extent of refinements required, typically ranging from 20 to > 100 trays.¹⁷ Unfortunately, patients often lack proper disposal instructions, leading to the commingling of these trays with other household waste.³ Consequently, the trays are frequently incinerated alongside general plastic waste, the most common method of plastic waste disposal. In addition, the waste generated after thermoforming of aligners in the manufacturing units shares a similar fate, further contributing to the volume of incinerated plastic waste.

SI:99 Formula:C8H10 CAS:95-47-6 MolWeight:106 RetIndex:907
CompName:o-Xylene



SI:95 Formula:C8H12 CAS:0-00-0 MolWeight:108 RetIndex:0
CompName:OCTA-2,4,6-TRIENE \$\$ 2,4,6-OCTATRIENE



SI:98 Formula:C8H12 CAS:4982-20-1 MolWeight:108 RetIndex:0

CompName:CYCLOHEXANE, 1,4-BIS(METHYLENE)- \$\$ 1,4-DIMETHYLENECYCLOHEXANE \$\$ 1,4-BIS(METHYLENE)CYCLOHEXANE \$\$ CYCLOHEXANE, 1,4

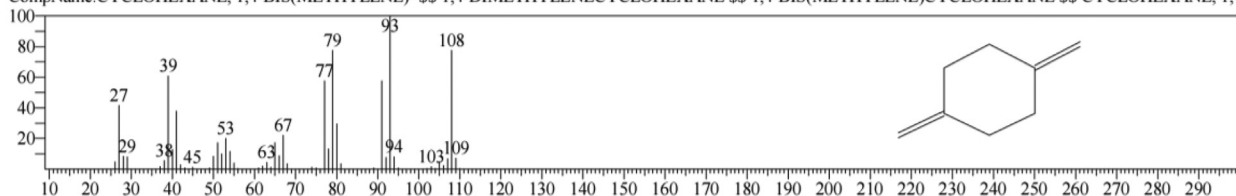


Fig 3. Mass spectra of the compounds with maximum concentration in PET-G sample.

SI:98 Formula:C6H6 CAS:71-43-2 MolWeight:78 RetIndex:0

CompName:BENZENE \$\$ CYCLOHEXATRIENE \$\$ (6)ANNULENE \$\$ A13-00808 \$\$ ANNULENE \$\$ AROMATIC ALKANE \$\$ BENZEEN \$\$ BENZEEN [DUTCH] \$\$ I

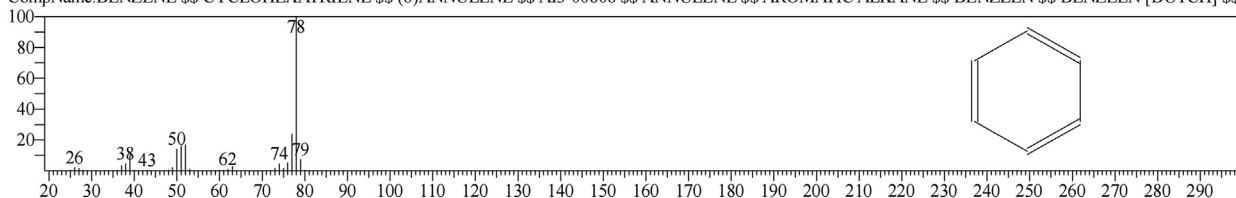


Fig 4. Mass spectrum of benzene in PET-G sample.

This investigation, thus, aimed to elucidate the chemical composition of the effluent smoke generated during the incineration of CA trays. Leveraging the commonly used GC-MS technique, the compounds were identified through comparative analysis with established standards and an extensive component library.⁸ The research targeted the 2 predominant aligner compositions, PET-G and polyurethane, to provide a comprehensive understanding of their combustion by-products.

Each of the 2 samples, when subjected to GC-MS analysis, was composed of 20 compounds with distinct

compositional profiles. Four among them were found common to both samples. O-xylene showed the maximum concentration in the PET-G sample, whereas 1,4-dimethyl-1,3-cyclohexadiene in polyurethane. Notably, the latter was 1 of the 4 compounds present in both samples, but the concentration was different. It was 18.88% (the highest) in polyurethane and 3.66% in PET-G.

The initial 2 peaks in the PET-G sample corresponded to benzene and toluene, respectively. These compounds were also identified during the GC-MS analysis of

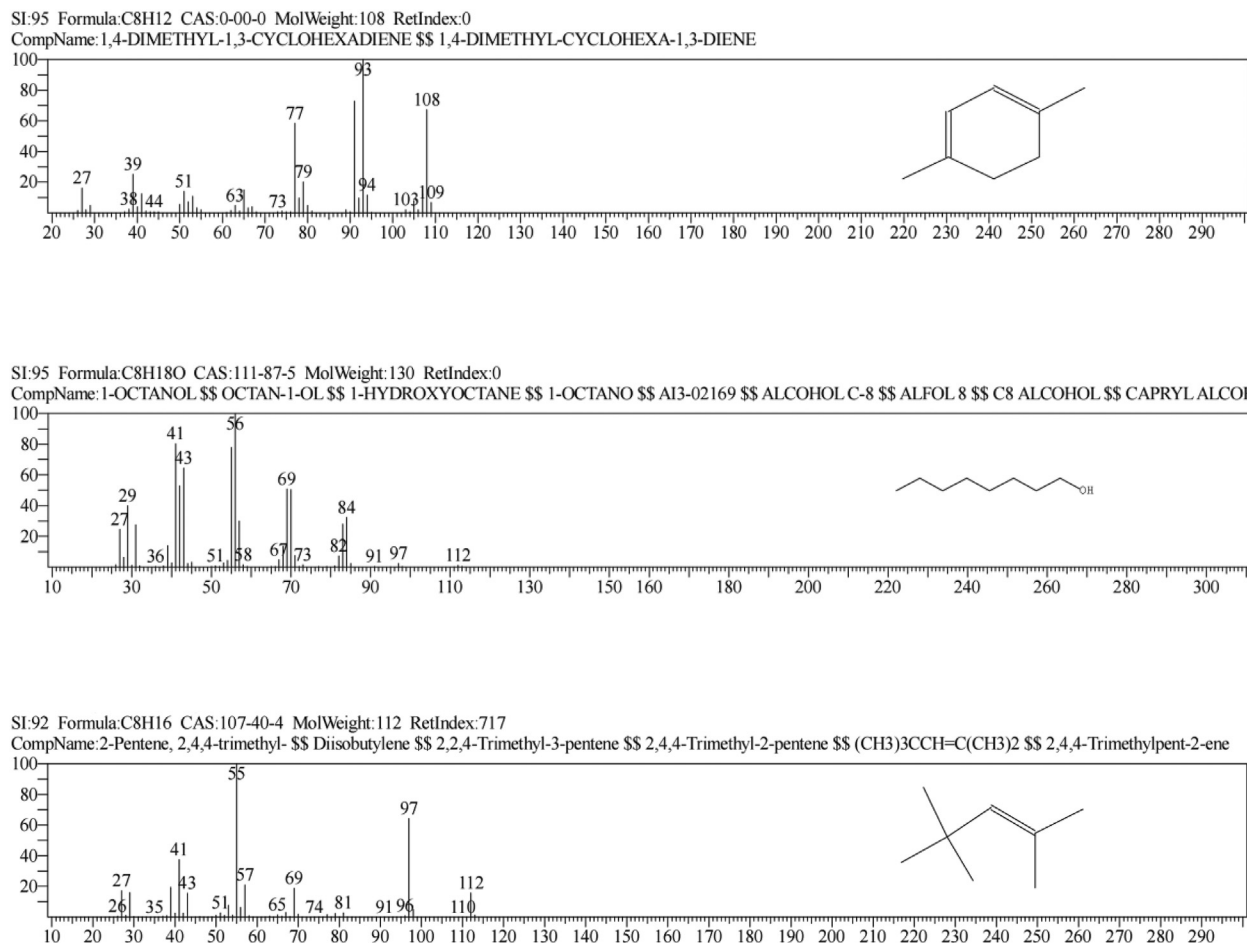


Fig 5. Mass spectra of the compounds with maximum concentration in the polyurethane sample.

polypropylene and polystyrene, as documented by Sarker et al.¹⁸ This cross-sample detection underscores the pervasive presence of benzene and toluene across various polymer matrices.

Benzene, detected at a concentration of 5.88% in the PET-G sample, is reported to cause serious health hazards. Prolonged exposure is primarily associated with adverse effects on the bone marrow, leading to aplastic anemia. Benzene is classified as a group 1 carcinogen by the International Agency for Research on Cancer.¹⁹ Long-term exposure is linked to an increased risk of developing leukemia, particularly acute myeloid leukemia, as well as other blood disorders such as myelodysplastic syndrome.²⁰ The meta-analysis by Zhou et al²¹ in 2020 reported that concentrations of benzene even $<3.25 \text{ mg/m}^3$ were associated with genetic damage, underscoring its potential for harm even at low exposure levels.

Tetrahydrofuran, corresponding to the first peak in the polyurethane sample at 8.13%, is a suspected

carcinogen and can cause respiratory irritation, nausea, headache, dizziness, and severe central nervous system depression.²² Other compounds found in the polyurethane sample, such as cyclotetrasiloxane, octamethyl- and 1,2-benzenedicarboxylic acid, bis(2-methylpropyl) ester, may impair fertility or harm the fetus.²² Benzene, 1,3-dimethyl- or xylene (also in the polyurethane sample), and o-xylene (in the PET-G sample) can be fatal if swallowed and enter the airways, with the former causing serious eye damage, as well.^{22,23} Breathing in high concentrations of o-xylene vapors can cause respiratory irritation, nausea, headache, dizziness, and central nervous system depression, similar to tetrahydrofuran.²²

Compounds such as 1-methylcycloheptene (in PET-G), and 2-pentene, 2,4,4-trimethyl- (in polyurethane) are severe irritants to skin, eyes, and respiratory system and potentially fatal if ingested.²² Toluene, in the PET-G sample, can cause irritation, dizziness, and headaches and long-term exposure can lead to serious

nervous system and reproductive health issues.²⁴ 6-Methyl-3-cyclohexenecarboxaldehyde (also in the PET-G sample) poses risks of serious eye damage and respiratory allergies or asthma.²² Nearly all identified compounds are found to be skin, eye, and respiratory irritants.²²

The World Health Organization reported that ambient air pollution is linked to 3.7 million deaths annually,²⁵ with open burning potentially accounting for up to 20% of these fatalities.²⁶ Reyna-Bensusan et al²⁷ identified PET and polystyrene contributing to the staggering 90% of the black carbon emissions produced by burning plastic waste. Unfortunately, both these materials are also involved in CA fabrication. An astounding 17 million patients worldwide have been treated with Invisalign, as per the latest update.²⁸ The count will escalate further when factoring in other aligner manufacturers, as well. The 3D-printed models used for thermoforming conventional aligner trays pose an additional environmental burden as they follow the same methods of disposal. Thus, CAT can contribute to a significant carbon footprint because of emissions from thermoplastic material extraction, manufacturing processes, global distribution, and waste disposal.^{7,29} These figures underscore the alarming situation in orthodontic care regarding plastic waste generation.

Mechanical recycling of small plastics such as aligners and their packaging is often not favored because the energy required for recycling frequently exceeds the material return.³⁰ Alternative recycling methods include chemical degradation techniques (eg, glycolysis, hydrolysis, and aminolysis), feedstock recycling (pyrolysis, gasification, and hydrogenation), and biological degradation (microbial degradation, using bacteria and fungi, and enzymatic degradation).³¹⁻³³ Among these, glycolysis and gasification are widely implemented on an industrial scale, whereas other techniques are still in the research and development stage but hold significant potential for sustainable recycling practices.³¹

Possible ways to mitigate the environmental burden

Recognizing the limitations of aligner systems and using this knowledge for proper case selection and treatment planning is crucial. Developing biodegradable and eco-friendly aligner materials is a promising strategy to reduce the environmental impact. At the production level, implementing more efficient manufacturing processes to minimize waste and energy consumption can significantly lower the overall carbon footprint.³⁰ Using direct 3D-printing techniques for aligner production can further reduce material waste and enhance production efficiency.

Ordering trays in batches can minimize waste in instances of tracking failure, especially in complex cases.³⁰ Mandatory warnings in aligner packages pertaining to its return after use can be inscribed and insisted on for effective and sustainable disposal.

Clinicians can further contribute to sustainability efforts by setting up 'used aligner collection points' for both commercially supplied and in-house aligners, fostering responsible disposal practices. Gupta et al³⁴ have developed a protocol for discarding used aligners, which involves cleaning and disinfecting the trays using ultrasonic and ultraviolet cleaning devices or chemicals (baking soda and water), followed by packing them in zip lock covers and disposing of them in red bags in accordance with biomedical waste management protocols. These aligners can then be recycled using any of the previously mentioned methods.

This study, thus, sheds light on the pressing environmental and health concerns associated with aligner disposal. Given the widespread adoption of CAT, the study highlights the urgent need for sustainable waste disposal practices within orthodontic care. Although recycling initiatives by some of the leading aligner manufacturers are a step in the right direction, their current effectiveness is limited. The newer direct-printed aligners offer advantages by obviating the need for 3D-printed models; however, the disposal of resin-based used trays continues to pose challenges. Therefore, orthodontists must actively engage in educating patients and promoting proper disposal practices. In addition, regulatory frameworks necessitate stringent mandates to address this exigent issue. This synergistic effort can potentially mitigate the adverse environmental and public health impacts of CAs.

Limitations and future direction

This study focused only on 2 commonly used thermoplastic materials in conventional aligner fabrication. Future studies may expand to encompass materials with varying compositions to provide a broader understanding. The environmental sustainability of direct 3D printed aligners using clear photopolymerisable resin materials also needs probing. Moreover, further investigations are warranted to elucidate the potential toxicologic effects of the myriad compounds released during the combustion of these materials.

CONCLUSIONS

The study identified a wide range of combustion by-products generated from the incineration of 2 distinct types of aligners. Importantly, PET-G aligners released benzene, categorized as a group 1 carcinogen,

whereas polyurethane aligner trays released tetrahydrofuran, a potential carcinogen. Some of the detected compounds were hazardous, whereas most were irritants to the skin, eyes, and respiratory system. These results underscore the critical need for health care providers to implement and adhere to stringent protocols for the safe and environmentally responsible disposal of aligners.

AUTHOR CREDIT STATEMENT

Elbe Peter contributed to conceptualization, methodology, formal analysis, funding acquisition, and manuscript review and editing; J. Monisha contributed to data curation and original draft preparation; V.P. Sylas contributed to methodology and formal analysis; and Suja Ani George contributed to supervision and manuscript review and editing.

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