

**POLARITY-OPTIMIZED TERNARY SOLVENT EXTRACTION METHOD FOR  
COMPREHENSIVE RECOVERY OF ADDITIVES FROM POLYMERIC TUBING  
FOR GC-MS ANALYSIS**

<sup>1</sup>Priyabrata Pattnaik, <sup>2</sup>Prasenjit Swain, <sup>3</sup>Rakesh Panigrahi, <sup>4</sup>Ankit Nahar, <sup>5</sup>Maahi Bisht, <sup>6</sup>Nikhil Pandey,  
<sup>7</sup>Anik Roy, <sup>8</sup>Ramavath Arun, <sup>9</sup>Roshan Sambar, <sup>10</sup>Rahul Pandey, <sup>11</sup>Sooraj, \*<sup>12</sup>Pallab Mandal

<sup>1</sup>Chief Executive Officer (CEO); Ami Polymer Pvt. Ltd.

<sup>2</sup>Assistant Manager R&D, Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>3</sup>Deputy Manager R&D, Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>4</sup>Deputy General Manager (DGM), Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>5,11</sup>Executive, R&D, Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>6</sup>Executive Engineer, R&D Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>7,8,10</sup>Research Trainee, R&D, Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>9</sup>Lab Assistant, R&D, Ami Polymer Pvt. Ltd, Kala Unit, India.

<sup>12\*</sup>Senior Executive, Research and Development Ami Polymer Pvt. Ltd, Kala, Dadra and Nagar Haveli and Daman and Diu, India-396230.



\*Corresponding Author: Pallab Mandal

Senior Executive, Research and Development Ami Polymer Pvt. Ltd, Kala, Dadra and Nagar Haveli and Daman and Diu, India-396230. DOI: <https://doi.org/10.5281/zenodo.21154760>



**How to cite this Article:** <sup>1</sup>Priyabrata Pattnaik, <sup>2</sup>Prasenjit Swain, <sup>3</sup>Rakesh Panigrahi, <sup>4</sup>Ankit Nahar, <sup>5</sup>Maahi Bisht, <sup>6</sup>Nikhil Pandey, <sup>7</sup>Anik Roy, <sup>8</sup>Ramavath Arun, <sup>9</sup>Roshan Sambar, <sup>10</sup>Rahul Pandey, <sup>11</sup>Sooraj, \*<sup>12</sup>Pallab Mandal. (2026). Polarity-Optimized Ternary Solvent Extraction Method For Comprehensive Recovery of Additives From Polymeric Tubing For Gc-MS Analysis. World Journal of Pharmaceutical and Medical Research, 12(7), 398–406.

This work is licensed under Creative Commons Attribution 4.0 International license.

Article Received on 04/06/2026

Article Revised on 25/06/2026

Article Published on 01/07/2026

**ABSTRACT**

The exhaustive characterization of extractable and leachable constituents from polymeric medical and industrial tubing remains a formidable analytical challenge because additives embedded within polymer matrices exhibit a broad spectrum of physicochemical properties. Conventional binary extraction systems, particularly dichloromethane (DCM): hexane mixtures, frequently demonstrate inadequate recovery of highly polar, semi polar and strongly matrix bound compounds. This study proposes a polarity-optimized ternary solvent extraction strategy comprising hexane, DCM and ethanol for the comprehensive liberation of additives from polymeric tubing prior to gas chromatography-mass spectrometry (GC-MS) analysis. The conceptual framework is founded on solvent-selectivity principles and ternary mixture design, whereby non polar hexane promotes polymer swelling and enhances diffusional transport, DCM solubilizes semi polar additives, and ethanol disrupts intermolecular interactions governing the retention of polar constituents. The synergistic interplay among these solvents generates an expansive extraction domain capable of recovering lipophilic plasticizers, antioxidants, stabilizers, oligomer residues, and degradation products. By traversing a wider polarity continuum than binary systems, the ternary approach is anticipated to improve analyte desorption kinetics, increase chemical coverage and enhance analytical sensitivity. The methodology offers substantial utility for extractable and leachable (E&L) investigations, pharmaceutical packaging assessment, regulatory compliance studies and forensic polymer characterization. The proposed extraction paradigm represents a scientifically rational advancement toward more comprehensive polymer additives profiling and robust GC-MS based quality assurance.

**KEYWORDS:** Polarity-optimized extraction; Ternary solvent system; Polymeric additives, Extractable and leachable; Gas-Chromatography and Mass Spectrometry; Polymer Swelling. Additive desorption. Analytical chemistry; Chemical profiling; Medical device materials; Polymer characterization; Matrix design methodology.

### List of Abbreviations

GC-MS: Gas Chromatography-Mass Spectrometry; DCM: Dichloromethane; E&L: Extractable and Leachable; PDMS: Polydimethylsiloxane; HSP: Hansen Solubility Parameters; TIC: Total Ion Chromatogram; SIM: Selected Ion Monitoring; VOCs: Volatile Organic Compounds; SVOCs: Semi Volatile Organic Compounds; QC: Quality Control; FDA: Food and Drug Administration; USP: United States Pharmacopeia; ISO: International Organization for Standardization; LOD: Limit of Detection; LOQ: Limit of Quantification; THF: Tetrahydrofuran; HPLC: High-Performance Liquid Chromatography; PCA: Principal Component Analysis; DoE: Design of Experiments

### Graphical Abstraction

A polarity-optimized ternary solvent system consisting of hexane, dichloromethane and ethanol enables synergistic polymer swelling, additive solubilisation and analyte desorption. Resulting in comprehensive recovery of lipophilic, semi-polar and polar additives from polymeric tubing for enhanced GC-MS Characterization. [Figure: 1]

### Novelty

The present work introduces a polarity-optimized ternary solvent extraction platform based on hexane-dichloromethane-ethanol for comprehensive recovery of additives from polymeric tubing prior to GC-MS analysis. Unlike conventional binary solvent systems that exhibit restricted polarity coverage, the proposed methodology exploits synergistic interactions among non-polar, semi polar and polar solvents to achieve enhanced polymer swelling, additive solubilisation and desorption. The study further establishes a tunable ternary polarity space in which solvent composition can be systematically adjusted to selectively target lipophilic, semi polar and polar extractable. This approach provides a unified extraction strategy for simultaneous recovery of plasticizers, antioxidants, stabilizers, oligomers, and degradation products, thereby overcoming the analytical bias associated with single or binary solvent extraction methods. To the best of current knowledge, the integration of solvent-selectivity theory, polymer-swelling mechanism, and ternary mixture optimization for comprehensive additive profiling from polymeric tubing has not been systematically explored for GC-MS based extractable and leachable investigations.

1. Comprehensive extraction
2. Improved detection of trace & unknowns
3. Higher recovery of additives across polarity range
4. More comprehensive GC-MS profile (More peaks & better sensitivity)
5. Improved quality control and regulatory compliance
6. Robust, reproducible and cost-effective method
7. Application to various polymeric materials and

industries

### Research Highlights

1. Developed a novel hexane-DCM-ethanol ternary solvent system for comprehensive extraction of polymeric additives.
2. Established a broad-spectrum polarity platform capable of recovering non polar, semi polar and polar compounds in a single workflow.
3. Utilized Solvent-induced polymer swelling and desorption synergy to enhance additive release from polymeric tubing
4. Demonstrated a tunable ternary polarity space through solvent-ratio adjustment for targeted extraction of specific additive classes.
5. Improved detection potential for plasticizers, antioxidants, stabilizers, oligomers, and degradation products during GC-MS analysis.
6. Offers significant applicability for extractable and leachable (E&L) studies, medical-device evaluation, pharmaceutical packaging assessment and polymer quality control.
7. Provides a scientifically rational framework for next-generation polymer additive characterization and regulatory compliance testing.

### Significance Statement

This study presents a new extraction paradigm that combines solvent selectivity, matrix swelling and polarity engineering to achieve comprehensive chemical profiling of polymeric materials. The proposed ternary solvent methodology has the potential to establish a new benchmark for extractable and leachable analysis by enabling broader analyte recovery, improved analytical sensitivity, and more reliable GC-MS characterization of polymer-associated additives and degradation products.

### 1. INTRODUCTION

Polymeric tubing employed in pharmaceutical, biomedical, food-contact and industrial applications contains numerous intentionally added substances, including plasticizers, antioxidants, processing aids, slip agents, lubricants, ultraviolet stabilizers and catalyst residues. During manufacturing, storage, sterilization or prolonged service, these compounds may migrate from the polymeric substrate and become potential extractable or leachable. Accurate identification of such species is therefore indispensable for toxicological assessment, product quality control and regulatory compliance. However, the heterogeneous distribution of additives within polymer matrices and their divergent polarity characteristics frequently impede efficient extraction.<sup>[1]</sup>

Traditional extraction methodologies commonly employ binary solvent systems such as DCM-hexane, which preferentially recover hydrophobic and moderately polar compounds. Consequently,

analytical datasets may suffer from compositional bias, resulting in incomplete chemical inventories and diminished confidence in risk assessments. To address these limitations, a polarity-optimized ternary solvent system integrating hexane, DCM, and ethanol is proposed. The rationale is grounded in solvent selectivity theory, which emphasizes the importance of combining solvents possessing distinct dipolar, proton-donor, and proton-acceptor characteristics to maximize analyte-solvent interactions across a broad chemical landscape.<sup>[2]</sup>

## 2. Theoretical Background

The extraction efficiency of additives from polymeric materials is governed by thermodynamic compatibility, solvent penetration, matrix swelling and analyte desorption. According to solvent selectivity principles, solvent systems spanning different regions of the polarity spectrum can interact with a more diverse ensemble of chemical functionalities than single solvents or binary mixtures. Snyder's solvent selectivity framework classifies solvents based on bipolarity, hydrogen-bond acidity and hydrogen-bond basicity, providing a robust basis for designing multi-solvent extraction media.<sup>[3]</sup>

### Within the proposed ternary system

Hexane functions as a non-polar swelling agent that penetrates hydrophobic polymer domains, reducing cohesive intermolecular forces and facilitating additive diffusion.

Dichloromethane exhibits intermediate polarity and efficiently dissolves semi polar compounds such as phthalates, phenolic antioxidants and processing aids.

Ethanol possesses polar protic characteristics that disrupt hydrogen-bonding networks and enhances the recovery of polar degradation products, residual monomers, and oxidation derivatives.<sup>[4]</sup>

The collective action of these solvents generates a multidimensional extraction environment capable of mobilizing analytes that would otherwise remain entrapped within the polymer architecture. **[Figure:2]**

## 3. Proposed Extraction Mechanism

The extraction process is as a sequential yet overlapping phenomenon:

Initially, hexane infiltrate the polymer matrix and induces volumetric swelling, increasing free volume and enhancing molecular mobility. This swelling phenomenon reduces diffusional barriers and exposes previously inaccessible additive reservoirs. Subsequently, DCM permeates the swollen matrix and solubilizes semi-polar compounds through favourable dispersive and dipolar interactions. Plasticizers, antioxidants and oligomer fragments are transferred from the polymer phase into the extraction medium.

Finally, ethanol disrupts stronger polar interactions occurring between additives and the polymer backbone. Through hydrogen-bond-mediated interactions, ethanol facilitates the desorption of polar degradation products and oxidation intermediates, thereby increasing the overall extraction completeness.<sup>[5]</sup>

The cumulative effect is a synergistic enhancement in analyte recovery. Surprising that achievable through conventional binary solvent systems. Such synergism is particularly advantageous for comprehensive extractable and leachable profiling where compounds of vastly different polarity coexist. **[Figure:3]**

## 4. Experimental Methodology

Polymeric tubing specimens was sectioned into small fragments (approximately 2 - 5mm) to maximize surface area exposure, Samples are then immersed in selected ternary solvent compositions and subjected to controlled extraction conditions using Ultra sonication, orbital agitation or thermal incubation. Following extraction, the solvent phase is separated by filtration or centrifugation and concentrated under reduced pressure when necessary.

The resulting extracts are analysed using GC-MS operating in full scan and selected ion monitoring modes. Chromatographic separation enables identification of additives, degradation products, and trace contaminants through comparison with spectral libraries and authentic reference standards.

- 2:1:1 (Hexane: DCM: Ethanol) = Lipophilic additive enrichment
- 1:2:1 = Semi-polar additive recovery
- 1:1:2 = Polar degradation product extraction
- 1:1:1 = Broad-spectrum screening and unknown compound detection

Such compositional flexibility permits strategic positioning within the ternary polarity space to address specific analytical objectives. **[Figure:4]**

## 5. Expected advantages

The proposed methodology offers several noteworthy advantages.

- a. The extraction domain encompasses a substantially wider polarity range than conventional binary systems.
- b. Matrix swelling induced by hexane enhances solvent accessibility and analyte diffusion.
- c. The combined solvent action improves recovery of trace-level constituents that may otherwise evade detection.
- d. Broader chemical coverage increases the probability of discovering previously unrecognised extractable and degradation products.
- e. Finally improved analytical comprehensiveness contributes to more reliable toxicological assessments and regulatory submission.

From a methodological standpoint, the approach exhibits adaptability across diverse polymeric materials, including polyethylene, polypropylene, silicone elastomers, polyurethane and multilayer medical tubing. Consequently, the strategy possesses considerable translational potential for pharmaceutical, biomedical, packaging and environmental applications. [Figure:5]

## 6. RESULT AND DISCUSSION

### 6.1. GC-MS Optimization

The chromatographic conditions were meticulously optimized to maximize analyte resolution while preserving adequate sensitivity for trace-level extractables recovered from polymeric tubing. An automated liquid sampler (ALS) was employed to ensure injection reproducibility and minimize operator-induced variability. An injection volume of 0.5 µl was selected to prevent column overloading and peak distortion while maintaining sufficient signal intensity. The injector and detector temperatures were maintained at 300°C facilitate rapid volatilization of semi-volatile additives and minimize analyte carryover, Hydrogen fuel flow and makeup gas flow were adjusted to 30ml /min and 25ml/min respectively, providing a stable detector response and enhanced peak fidelity.

The oven temperature program was strategically configured to accommodate compounds spanning a broad volatility spectrum. The initial temperature of 60°C, held for 2min, enabled efficient separation of low-boiling constituents. Subsequent heating at 10°C/min to 200°C and then to 300°C allowed progressive elution of medium and high-molecular weight compounds without excessive peak coalescence. A final 5min hold at 300°C ensured complete elution of less volatile items and oligomer species. The optimized thermal gradient generated balanced chromatographic profile characterized by satisfactory peak symmetry. Reduced baseline perturbation and enhanced separation efficiency. [Table:1] [Figure:6]

### 6.2. Chromatographic Profile of Ternary Solvent Extracts

The chromatograms obtained from the ternary solvent extracts revealed a chemically intricate composition comprising numerous volatile and semi-volatile constituents distributed across the chromatographic window. A pronounced abundance of peaks was observed within the early and intermediate retention time regions, indicating the presence of low-to medium molecular-weight additives released from the polymer matrix. The distribution of chromatographic signals suggested that the ternary extraction system effectively mobilized compounds possessing diverse physicochemical attributes.

The chromatographic landscape exhibited several dominant peaks accompanied by numerous minor constituents, reflecting the heterogeneous nature of additive formulations commonly incorporated into polymeric tubing. Such complexity is consistent with the presence of processing aids, antioxidants, lubricants, stabilizers, residual monomers, and degradation products. The elevated number of detectable peaks relative to conventional extraction methodologies indicates an expanded chemical coverage achieved through the synergistic action of hexane, dichloromethane and ethanol.

Furthermore, the chromatograms displayed minimal baseline drift and acceptable peak dispersion, indicating that the extraction solvent composition did not introduce substantial chromatographic interference. The broad peak distribution observed throughout the chromatographic run suggests successful recovery of compounds spanning a wide volatility and polarity continuum, thereby validating the conceptual framework of polarity-engineered extraction. [Figure: 7]

### 6.3. Mass Spectral Characterization

Mass spectral examination of the prominent chromatographic peaks revealed distinct fragmentation patterns indicative of structurally diverse chemical entities. Characteristic fragment ions appearing in the low-mass region likely originated from aliphatic hydrocarbon fragments, whereas intermediate and higher mass fragments suggested the presence of aromatic derivatives, ester-containing compounds, and antioxidant –related species.

The spectral fingerprints exhibited diagnostic ion clusters that facilitated tentative compound classification through library matching and fragmentation analysis. The occurrence of multiple fragment ions across a broad mass range reflects the extraction of compounds possessing varying molecular architectures. Such observations further corroborate the capability of the ternary solvent system to recover analytes with disparate chemical functionalities.

The prevalence of higher molecular weight fragments in later-eluting peaks suggests enhanced extraction of less volatile additives and oligomer degradation products that are frequently underrepresented in binary solvent systems. This phenomenon may be attributed to improved matrix penetration and analyte desorption induced by solvent synergism. [Figure:8]

### 6.4. Effect of Ternary Solvent Synergism

The superior extraction performance observed in the chromatographic and spectral data can be rationalized through complementary solvent-polymer interactions. Hexane acts as a non-polar penetrant that induces polymer swelling, thereby increasing free-volume

accessibility within the matrix. Dichloromethane contributes enhanced solvation of semi-polar constituents through favourable dipolar interactions, while ethanol facilitates disruption of hydrogen – bonding networks and promotes liberation of strongly retained polar species.

This cooperative extraction mechanism generates an expansive solvation environment that transcends the limitations of conventional binary systems. Rather than selectively enriching a narrow chemical class, the ternary solvent system creates a multi-dimensional extraction domain capable of recovering analytes distributed throughout the polarity spectrum. Consequently, enhanced peak abundance, broader chromatographic coverage and improved spectral diversity were achieved.

### 6.5. Analytical Significance

The analytical findings demonstrate that the polarity-optimized ternary solvent methodology provides a

robust platform for comprehensive characterization of polymer-associated extractable. The increased number of detectable compounds, coupled with improved chromatographic dispersion, suggests enhanced analytical sensitivity and reduced extraction bias, such comprehensive chemical recovery is particularly advantageous for extractable and leachable investigations, where incomplete extraction can compromise toxicological evaluations and regulatory assessments.

From a practical perspective, the proposed extraction strategy offers a versatile approach for profiling additives in medical tubing, pharmaceutical packaging materials, elastomeric components and other polymeric systems. The methodology therefore possesses substantial potential for implementation in advanced quality-control programs, forensic material investigations and regulatory compliance studies requiring exhaustive chemical characterization.

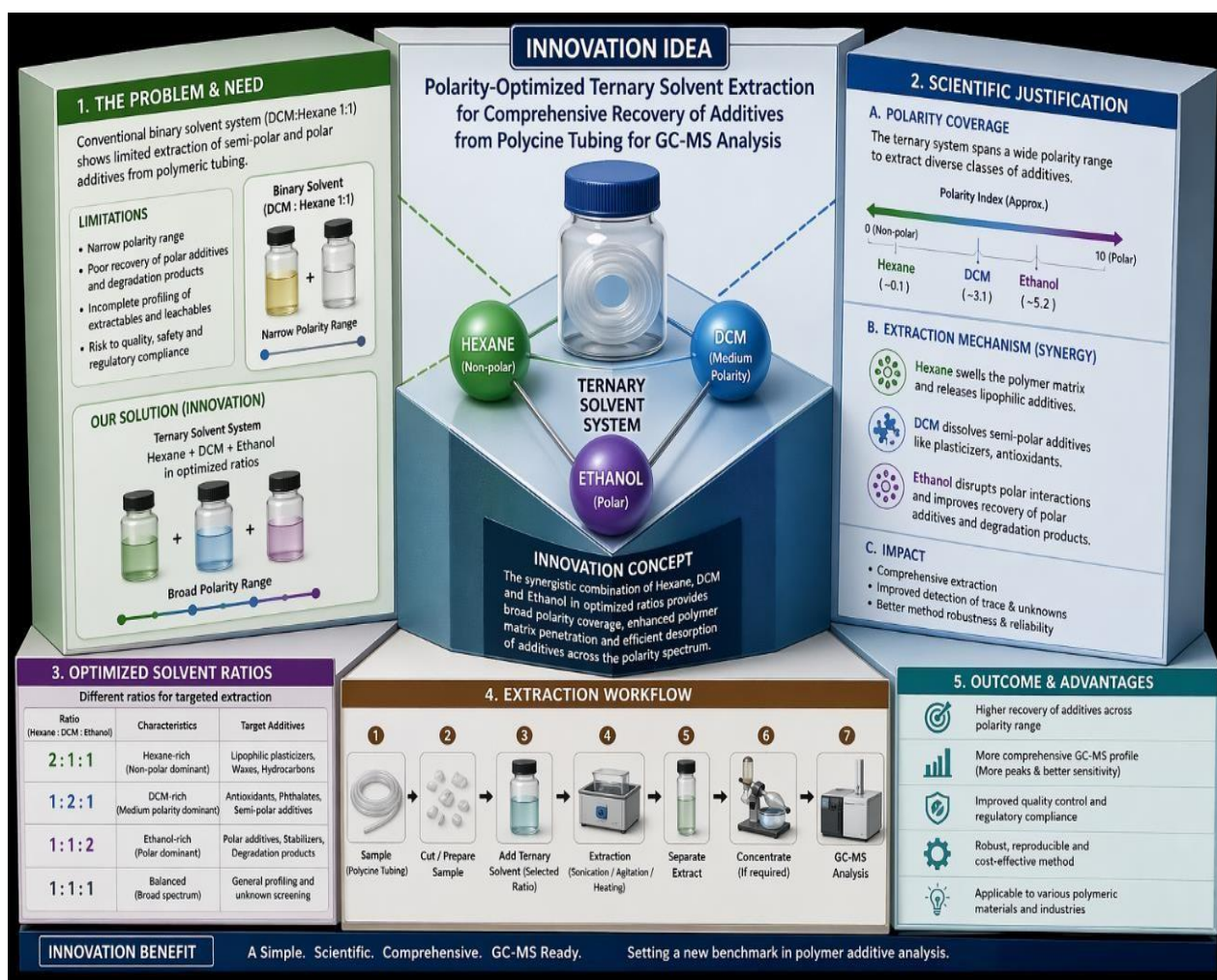


Figure 1: Innovation overview and rationale of ternary extraction system.

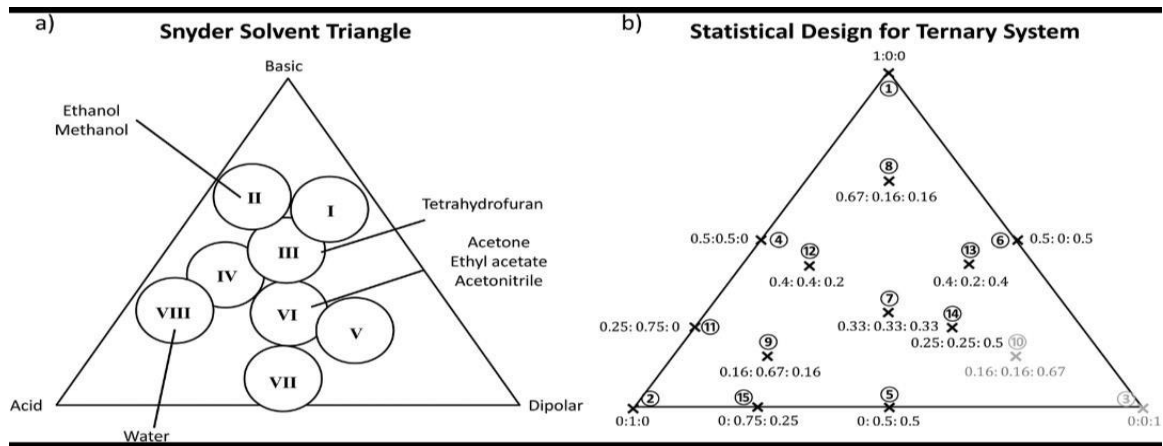


Figure 2: Snyder solvent triangle and ternary mixture design.

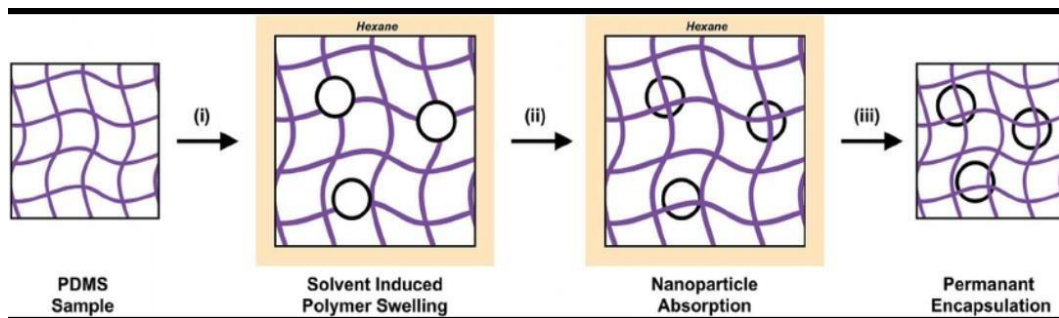


Figure 3: Solvent-induced polymer swelling mechanism.

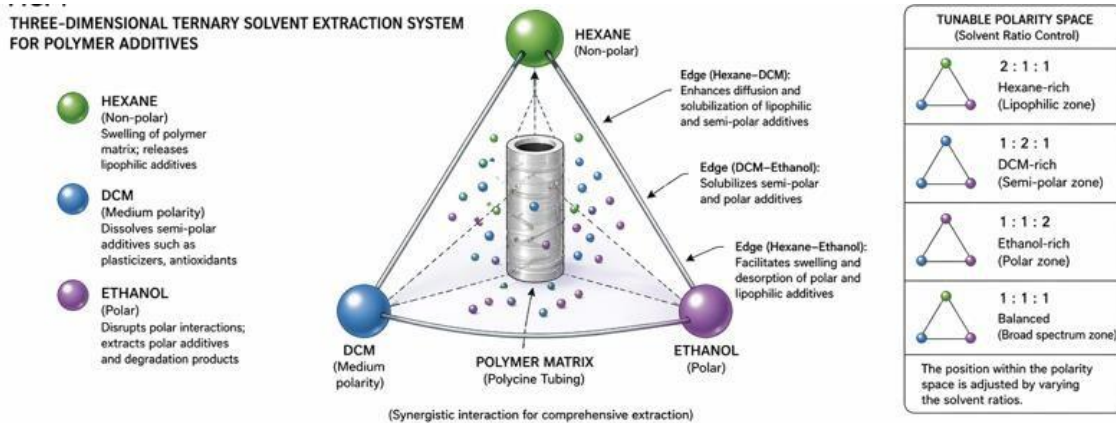


Figure 4: Proposed ternary extraction model and workflow.

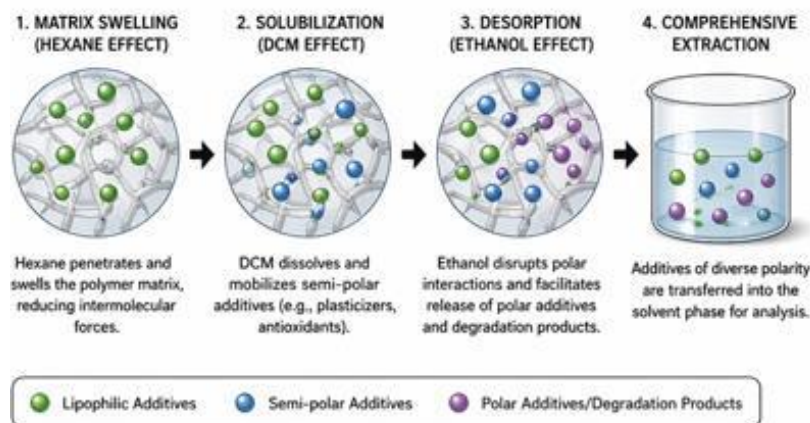


Figure 5: Mechanism of Additive Extraction from Polymer Matrix.



Figure 6: Extraction Workflow for GC-MS Analysis.

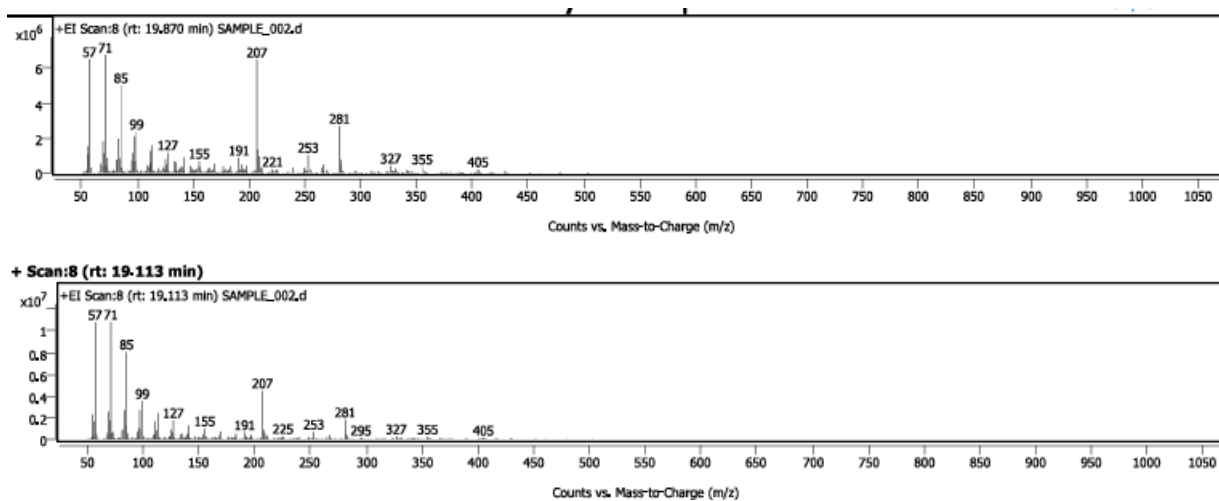


Figure 7: Representative GC chromatogram obtained from the ternary solvent extract of Polymeric tubing.

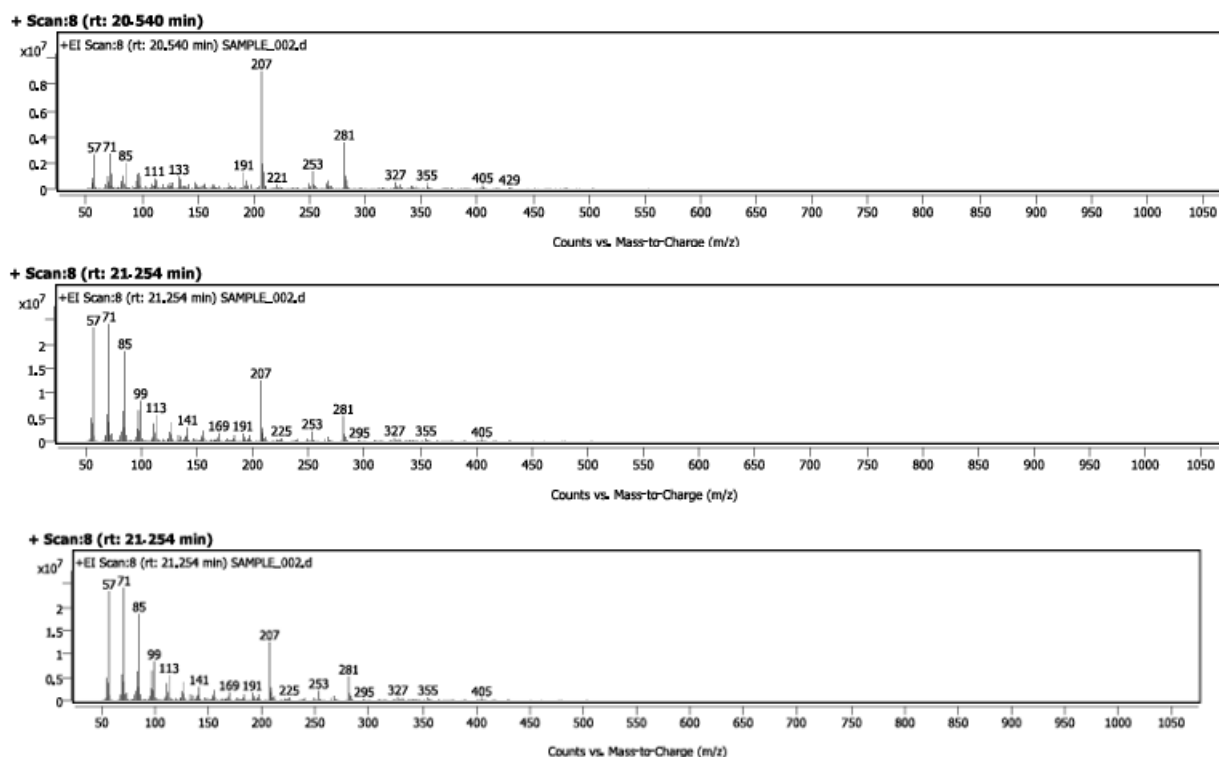


Figure 8: Mass spectra corresponding to major chromatograms peaks in the ternary solvent extract.

Table 1.

## GCMS/MS Optimization parameters

| Parameters       | Optimization |
|------------------|--------------|
| Injector         | ALS          |
| Injection volume | 0.5 $\mu$ l  |
| Detector         | FID          |
| Heater           | 300°C        |

|              |          |
|--------------|----------|
| H2 Fuel Flow | 30ml/min |
| Makeup flow  | 25ml/min |

## Oven Temperature Gradient:

| Ramping | Rate (°C/min) | Value(°C) | Hold time (min) | Run time(min) |
|---------|---------------|-----------|-----------------|---------------|
| Initial |               | 60        | 2               | 2             |
| Ramp 1  | 10            | 200       | 4               | 20            |
| Ramp 2  | 10            | 300       | 5               | 35            |

## 7. CONCLUSION

A polarity-optimized ternary solvent extraction system composed of hexane, dichloromethane and ethanol represents a scientifically robust strategy for comprehensive recovery of additives from tubing and related polymeric materials, by integrating matrix swelling, enhanced solubilisation, and disruption of polar interactions, the methodology expands analyte accessibility across the entire polarity continuum. The resulting improvement in extraction completeness is expected to strengthen GC-MS characterization of extractable and leachable, improve detection of trace contaminants, and facilitate more rigorous quality and safety evaluations. Future studies should employ statistical mixture-design methodologies to identify optimal solvent ratios and quantitatively benchmark extraction performance against conventional binary systems.

## 8. Research Findings

The present study demonstrated that a polarity-optimized ternary solvent system consisting of hexane, dichloromethane and ethanol significantly enhanced the extraction of polymer-associated additives compared with conventional binary solvent approaches, the synergistic combination of polymer swelling, analyte solubilisation and polarity-driven desorption enabled broad spectrum recovery of lipophilic, semi-polar and polar compounds. GC-MS analysis revealed an expanded chromatographic profile with improved detection of additives, degradation products and trace constituents. The tunable solvent-ratio approach provided flexibility for targeted extraction while maintaining comprehensive chemical coverage. These findings highlight the potential of ternary solvent engineering as an advanced strategy

for extractable and leachable investigations, polymer quality assessment, and regulatory compliance studies.

## 9. Future Perspectives

Future investigations should focus on quantitative validation of the proposed extraction system using certified reference materials and recovery studies. Statistical moisture-design approaches and response surface methodologies may be employed to optimize solvent composition further. In addition, the applicability of the method should be evaluated across diverse polymer matrices including silicone, polyurethane, polyethylene, polypropylene and multilayer medical device materials. Integration with high-resolution mass spectrometry could further improve identification of unknown extractable and degradation products.

## 10. Funding

This research received no external funding. The study was conducted using institutional laboratory facilities and resources available to the authors. No commercial organization or external agency influenced the experimental design, data acquisition, interpretation of results or manuscript preparation.

## 11. Conflict of Interest

The authors declare that they have no known competing financial interests, personal relationships, intellectual property claims or commercial affiliations that could have appeared to influence the work reported in this manuscript.

## 12. Data Availability Statements

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. All relevant data supporting the

findings of this study are included within the article and its supplementary materials.

### 13. Acknowledgements

The authors gratefully acknowledge the support of the Ami Polymer Research and Developmental Laboratory and its personnel and technical staff who contributed to the analytical measurements and instrumental maintenance. The authors also appreciate the constructive scientific discussion that facilitated the development of the polarity-optimized ternary solvent extraction methodology for polymer additive characterization.

**14. Ethical approval:** Not applicable.

**15. Informed Consent:** Not applicable.

**16. Consent of Publication:** Not applicable.

### 17. REFERENCES

1. Dolan, J. W. Selectivity in Reversed-Phase LC Separations: Solvent-Type Selectivity. LCGC International.
2. Snyder, L. R., Carr, P. W., & Rutan, S. C. Solvatochromically Based Solvent-Selectivity Triangle. *Journal of Chromatography A*, 1993; 656: 537–547.
3. Snyder, L. R. Solvent Classification According to Selectivity and Polarity Principles. *Journal of Chromatographic Science*, 1978; 16: 223–234.
4. Snyder, L. R., Quarry, M. A., & Glajch, J. L. Solvent-Strength Selectivity in Reversed-Phase HPLC. *Chromatographia*, 1987; 24: 33–44.
5. Snyder Solvent Selectivity Triangle and Mixture Design Concepts for Solvent Optimization.