CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 6, ISSUE 2, 2026, In-Press
DOI: https://doi.org/10.15282/construction.v6i2.14239

RESEARCH ARTICLE

Spectroscopic investigation of recycled PET modified with triacetin and ATBC plasticizers for sustainable polymer composite applications

S. I. Mohd Nazri[1], M. F. Mohamad Borhan[1], N. F. Ariffin[1]*, A. N. Salim Salmi[2], S. M. Syed Mohsin[1], G. A. Jokhio[3], M. A. Ismail[4]

[1]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia
[2]Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia
[3]Faculty of Engineering and IT, The British University in Dubai. Block 10 & 11, 1st and 2nd Floor, Dubai International Academic City, PO Box: 345015, Dubai, United Arab Emirates
[4]Department of Civil and Environmental Engineering, Brunel University London, London UB8 3PH, United Kingdom

Abstract: Plastic modification has emerged as a potential strategy for improving polymer processability and extending the functional use of recycled materials. Polyethylene terephthalate (PET) is widely used but presents significant environmental challenges because of its high durability and limited biodegradability. This study comparatively investigated the molecular-level interactions between recycled PET and two selected non-phthalate plasticizers, Triacetin and Acetyl Tributyl Citrate (ATBC), using Fourier Transform Infrared (FTIR) spectroscopy following thermal processing at approximately 300 °C. Triacetin was incorporated at 15, 30 and 40 wt.%, whereas ATBC was evaluated at 15 and 30 wt.%; the 40 wt.% ATBC formulation was excluded because a suitable intact specimen could not be obtained. FTIR spectra were analysed to identify changes in characteristic functional groups and to evaluate concentration-dependent spectral responses following plasticizer incorporation. Changes in the carbonyl, C–O, C–C–O and C–H absorption bands supported the physical incorporation of both plasticizers into the thermally processed PET system. The absence of new characteristic absorption bands suggested that the observed changes were predominantly associated with physical intermolecular interactions rather than the formation of new covalent functional groups. Semi-quantitative FTIR peak-ratio analysis further demonstrated concentration-dependent variations in selected absorption bands. At 30 wt.% plasticizer loading, the normalized C=O, C–O and C–C–O peak ratios were 1.20, 1.18 and 1.12, respectively, for Triacetin-modified PET, compared with 1.35, 1.30 and 1.25 for ATBC-modified PET. These results indicate that ATBC produced a higher normalized spectral response than Triacetin at the same concentration; however, the differences should not be interpreted as conclusive evidence of superior plasticization efficiency or long-term stability. The findings provide preliminary molecular-level insight into the interactions between recycled PET and the selected plasticizers. Further thermal, rheological, mechanical, migration, ageing and durability assessments are required to determine the practical suitability of modified PET for polymer concrete and other construction composite applications.

Article History
Received :
Revised :
Accepted :
Published :

Keywords
Spectroscopic analysis
Fourier Transform Infrared Spectroscopy (FTIR)
Polyethylene Terephthalate waste
Triacetin
Acetyl Tributyl Citrate

1. Introduction

Plastics have become indispensable materials in modern society because of their versatility, durability and cost-effectiveness. They are widely used across industrial and consumer sectors, including packaging, construction and transportation. However, the same properties that make plastics highly valuable also create significant environmental challenges, as their resistance to degradation contributes to persistent pollution and waste accumulation [1]–[2]. Among the various polymer types, polyethylene terephthalate (PET) is one of the most extensively used thermoplastics worldwide. PET is predominantly used in beverage bottles, textile fibres and packaging materials [3]–[4]. More than one million plastic beverage bottles are purchased every minute globally [5], highlighting the large scale of PET production and consumption.

The molecular structure of PET, which is characterised by a high aromatic content, provides excellent mechanical strength and resistance to microbial degradation [6]. Although these properties enhance its performance and stability, they also hinder biodegradation, leading to the accumulation of PET waste in landfills and marine ecosystems [7]. Approximately eight million tonnes of plastic waste enter the world's oceans annually, while a substantial proportion of plastic bottles remains unrecycled [8]. These environmental concerns have increased the need for effective and sustainable PET recycling and valorisation strategies.

The growing generation of PET waste has encouraged extensive research into recycling and recovery methods. According to Massoud and Dsilva [5], PET waste may generally be managed through disposal, incineration or recycling, as illustrated in Figure 2. Conventional recycling methods include mechanical and chemical recycling. However, repeated mechanical processing may result in polymer chain scission and deterioration of material properties, whereas chemical recycling methods commonly require high energy input, specialised processing conditions and costly catalysts [9]–[10].

***CORRESPONDING AUTHOR | N. F. Ariffin** | ✉ farhayu@umpsa.edu.my
© 2026 The Authors. Published by Universiti Malaysia Pahang Al-Sultan Abdullah Press. This is an open access article under the CC BY-NC 4.0 license

These limitations demonstrate the need for alternative approaches that improve the processability and potential reuse of recycled PET while maintaining its functional properties. In this context, polymer modification using plasticizers has emerged as a potential strategy for increasing polymer chain mobility, reducing brittleness and improving processability.

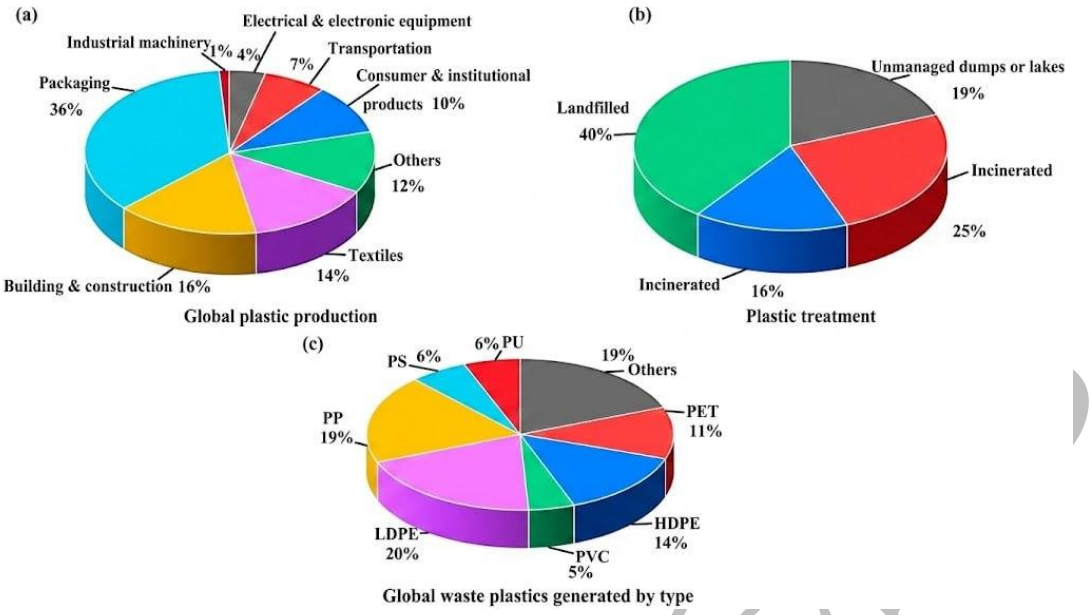


Figure 1. Global plastic data in 2022: (a) global plastic production, (b) plastic treatment and (c) global plastic waste generated by type [11]

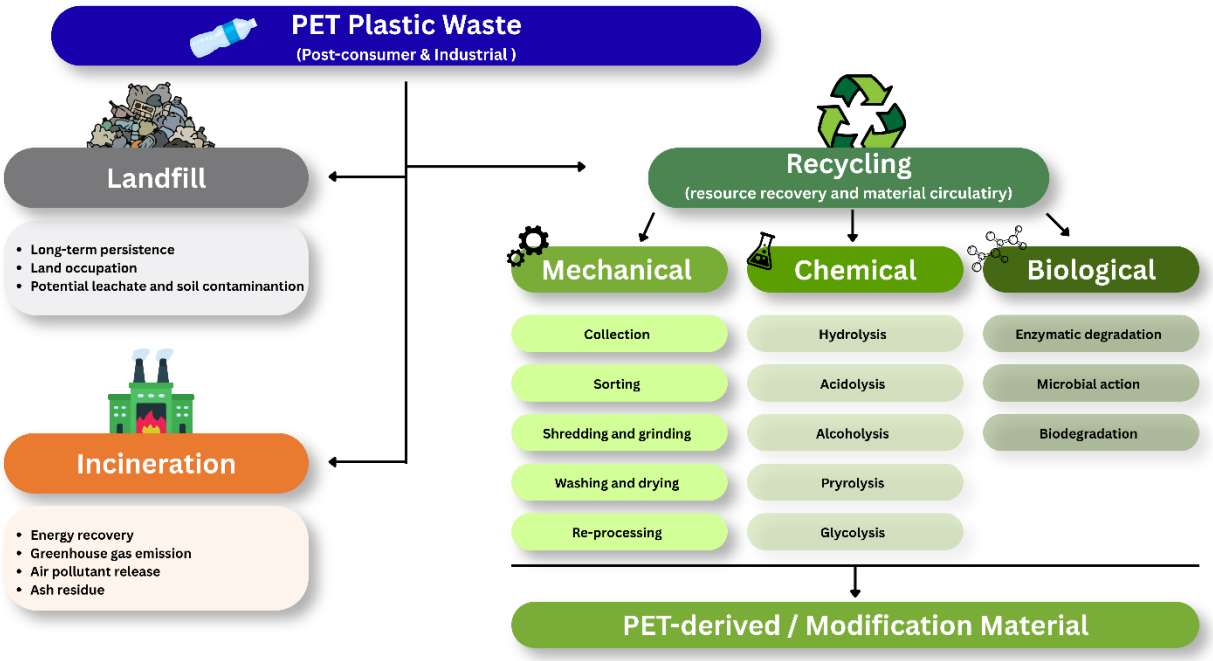


Figure 2. Flowchart of PET plastic waste management processes [5]

In recent years, recycled PET has been widely investigated for use in construction materials, primarily as an aggregate replacement, fibre reinforcement or raw material for unsaturated polyester-based polymer concrete [12]–[13], [14]. The replacement of natural fine or coarse aggregates with PET waste may provide environmental benefits by reducing the consumption of natural resources. However, high PET replacement levels are frequently associated with reduced compressive strength and weak interfacial bonding with cementitious matrices because of the hydrophobic nature and relatively low stiffness of PET particles [14].

Studies involving PET-derived resin in polymer concrete have also demonstrated promising strength and potential applications in precast products. Nevertheless, the long-term durability, microstructural stability and binder–aggregate compatibility of PET-based polymer concrete remain insufficiently characterised. Comparatively limited research has focused on the physical modification of recycled PET using plasticizer systems to improve its molecular compatibility and processability for potential use as a binder or matrix component in construction composites. In addition, molecular-

level investigations using spectroscopic techniques to evaluate the interactions between recycled PET and plasticizers remain limited.

The research gaps identified from previous studies are summarised in Table 1. The table highlights that most existing studies have concentrated on PET as an aggregate, fibre, cement replacement material or recycled resin. Research focusing specifically on plasticizer-modified recycled PET and its molecular interactions remains comparatively limited.

Table 1. Summary of research gaps

Author	Main Focus	Key Finding	Research Gaps
[3]	PET fibres in Portland cement and durability assessment	PET fibres may improve early-age toughness and impact resistance. However, their performance may deteriorate in alkaline cementitious environments during ageing.	The long-term durability and degradation mechanisms of PET fibres in alkaline cement matrices remain uncertain.
[15]	PET polymer waste in self-compacting concrete	Demonstrated the feasibility of incorporating PET waste into self-compacting concrete mixtures.	The study focused on PET as a constituent or replacement material rather than as a modified binder. Molecular-level interactions between modified PET and the surrounding matrix remain underexplored.
[16]	Surface-modified PET waste as a replacement for natural aggregate	Surface modification may improve the interaction between PET aggregate and the cementitious matrix.	Surface-modified PET aggregate may still exhibit weak bonding, while long-term durability under freeze–thaw exposure and chemical attack remains insufficiently studied. Binder-level modification of PET was not considered.
[17]	Recycled PET resin in polymer concrete and time–temperature behaviour	Demonstrated the potential of recycled PET resin for polymer concrete and characterised its time- and temperature-dependent behaviour.	Long-term durability under elevated temperature and sustained loading remains limited and validation has primarily been conducted at laboratory scale.
[18]	Gamma-irradiated PET waste as a partial cement replacement	Demonstrated the feasibility of using treated PET waste as a partial cement replacement in conventional concrete.	The long-term durability and performance of irradiated PET under service-relevant conditions were not fully evaluated.
[19]	Review of PET granules, fibres and aggregate replacement in concrete	Provided a broad review of fresh and hardened properties of PET-modified concrete.	Most studies considered PET as an aggregate or fibre, while the role of chemically or physically modified PET as a binder remains limited. Long-term degradation under combined service conditions also requires further investigation.
[20]	PET granules as a partial replacement for coarse aggregate	Demonstrated the feasibility of replacing part of the natural aggregate with PET granules.	High replacement levels resulted in strength reduction, while long-term durability was not sufficiently addressed.
[21]	Recycled PET fibres in concrete	Reported the effects of PET fibres on workability, compressive strength, tensile strength and flexural performance.	PET was used primarily as fibre reinforcement. The long-term interaction between PET fibres and the matrix, including degradation mechanisms, remains insufficiently understood.
[22]	Polymer concrete containing recycled PET resin for precast applications	Recycled PET resin demonstrated the potential to produce polymer concrete with high early strength and compressive strength.	Evidence for structural-scale applications and long-term behaviour under service loading remains limited.
[23]	Advanced PET recycling through photoreforming	Demonstrated an alternative pathway for PET valorisation into valuable monomers and hydrogen.	The method does not address the integration of recycled PET into structural or construction composite systems.

Recent studies have explored various approaches to improve PET recyclability and performance. Mechanical recycling remains the most widely used method; however, repeated processing may cause polymer chain scission, molecular-weight reduction and deterioration of material properties [9]. Chemical recycling methods, including glycolysis and methanolysis, can recover valuable monomers but commonly require high energy input, controlled reaction conditions and catalysts [10]. More recently, plasticizers and bio-based additives have been investigated as potential

In-Press

modifiers for improving the flexibility and processability of polymeric materials [24]. Triacetin and Acetyl Tributyl Citrate (ATBC) have previously been investigated as plasticizers for several polymers, including poly(vinyl alcohol) (PVA) [25], poly(lactic acid) (PLA) [26], poly(vinyl chloride) (PVC) [27], cellulose acetate and polyhydroxyalkanoates (PHA) [28]. Previous studies have generally focused on flexibility, processability, elongation and mechanical performance. However, comparatively limited attention has been given to the modification of recycled PET using Triacetin and ATBC under high-temperature melt-processing conditions.

The present study focuses on comparing two selected non-phthalate plasticizers, Triacetin and ATBC, in recycled PET. Conventional phthalate plasticizers were not included as comparative controls because the objective of this study was limited to evaluating the molecular interactions of these two selected plasticizers with thermally processed recycled PET. Therefore, the study does not claim to experimentally demonstrate their environmental superiority over conventional phthalate plasticizers. Instead, it provides a preliminary spectroscopic comparison of the interaction of Triacetin and ATBC with recycled PET. Although FTIR spectroscopy has been widely used to investigate polymer–plasticizer interactions, comparative spectroscopic studies of recycled PET modified with Triacetin and ATBC following thermal processing at approximately 300 °C remain scarce. This represents a relevant research gap because molecular-level information on plasticizer incorporation and interaction with recycled PET is important for understanding its potential processability and compatibility in PET-based construction composites.

Accordingly, this study aims to comparatively investigate the molecular interactions between recycled PET and Triacetin or ATBC at different concentrations using Fourier Transform Infrared spectroscopy following thermal processing at approximately 300 °C. The study evaluates changes in selected characteristic absorption bands associated with PET and the incorporated plasticizers. The findings are intended to provide preliminary molecular-level evidence of plasticizer incorporation and compatibility. However, conclusions regarding long-term stability, migration resistance, mechanical performance, durability and suitability for structural polymer concrete applications require further thermal, rheological, mechanical, migration and durability testing.

2. Materials

2.1 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET or PETE) is a widely used polymer in the polyester family. According to the International Union of Pure and Applied Chemistry (IUPAC) nomenclature, PET is scientifically known as poly(oxyethyleneoxyterephthaloyl) and consists of repeating monomer units of ethylene terephthalate ($C_{10}H_8O_4$), as shown in Figure 3. PET is a condensation polymer produced either through the polymerization of terephthalic acid (TPA) and ethylene glycol (EG) or via the transesterification of dimethyl terephthalate (DMT) with EG [7], [29]. PET plastics typically contain about 85% terephthalic acid (benzene-1,4-dicarboxylic acid, H_2BDC) monomer, which is an important industrial raw material [11].

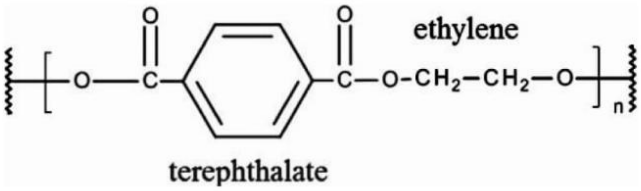


Figure 3. Chemical structure of PET [30]

The versatility and exceptional properties of PET have established its widespread use across industries such as packaging, textiles and engineering. Its mechanical strength, lightweight nature and chemical resistance make it particularly valuable for packaging applications [4]. In addition, PET's excellent barrier properties especially its resistance to CO_2 make it ideal for carbonated beverage containers, as it helps preserve product quality and extend shelf life. Unlike many other plastics, Unlike some other polymer systems, conventional PET is generally processed without the addition of external plasticizers [30].

The structure of PET is derived from two primary monomers: ethylene glycol and terephthalic acid [6], [11]. Through condensation polymerization, these monomers combine to form long repeating chains, producing the polymer PET. Terephthalic acid (TPA) also referred to as PTA, TA or p-phthalic acid is an aromatic dicarboxylic acid with the chemical formula $C_6H_4(COOH)_2$, as shown in Figure 4. The second monomer, ethylene glycol (EG), also known as ethane-1,2-diol, is a simple diol with the chemical formula $C_2H_6O_2$, as illustrated in Figure 5.

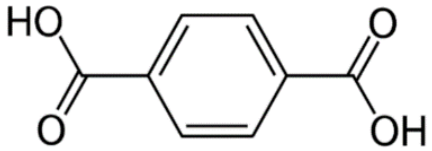


Figure 4. Chemical structure of TPA [30]

TPA serves as a fundamental raw material in the production of PET, polybutylene terephthalate (PBT), resins, synthetic fibers, films and engineering plastics. It is a white crystalline solid that is insoluble in water and ethanol. Global TPA production is approximately 40 million metric tonnes annually, with the purified TPA market valued at USD 46 billion in 2023 and projected to reach USD 80 billion by 2034, supported by a compound annual growth rate (CAGR) of 5.03% [30]. This growth is primarily driven by increasing demand from packaging and textile industries, rapid urbanization and rising living standards in the Asia-Pacific region. Furthermore, the recovery of TPA through PET hydrolysis offers significant economic opportunities and environmental benefits.

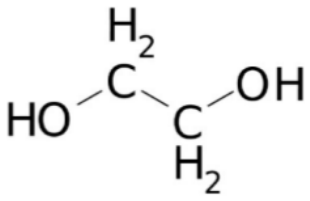


Figure 5. Chemical structure of EG [30]

EG is a colorless, odorless and viscous liquid with a sweet taste. It dissolves readily in polar solvents such as water, alcohol and acetone, but has limited solubility in non-polar solvents. Known for its antifreeze properties, EG is widely used in automotive and industrial applications [31]. It is also readily biodegradable, making it relatively environmentally friendly. Importantly, EG is a key monomer in the production of PET and is among the most abundantly produced diols worldwide. Global EG production has grown rapidly, from 30.24 million metric tonnes per annum (MMTPA) in 2014 to 60.6 MMTPA in 2023, with projections of 67.04 MMTPA by 2025 [30]. More than 58% of EG output is dedicated to PET manufacturing, underlining its central role in both PET production and recycling. In particular, EG plays a crucial role in chemical recycling processes such as hydrolysis and glycolysis [32]–[33], thereby supporting sustainability and resource efficiency in the polymer industry.

2.2 Plasticizers

Plasticizers are incorporated into polymers to extend their processing window and enhance flexibility [34]. However, this approach has limitations, as it reduces the service temperature of the final product by lowering the glass transition temperature [35]. The addition of plasticizers increases the free volume and segmental mobility of polymer chains, protects inter- and intra-macromolecular interactions and minimizes internal friction within the biopolymer [36]. In this study, two non-phthalate plasticizers were selected: Triacetin and Acetyl Tributyl Citrate (ATBC). Their selection was intended to enable a comparative spectroscopic evaluation of their interactions with thermally processed recycled PET. The present study does not experimentally compare their environmental performance with that of conventional phthalate plasticizers.

2.2.1 Triacetin

Triacetin is a triester of acetic acid and glycerol, as shown in Figure 6. It is also known by several other names, including glyceryl triacetate, glycerin triacetate, glycerine triacetate, triacetyl glycerine, acetin-tri, 1,2,3-triacetoxypropane, 1,2,3-propanetriol triacetate and acetic-1,2,3-propanetriyl ester [37]. More commonly, it is referred to as glycerol triacetate [38]. The properties of Triacetin are summarized in Table 2.

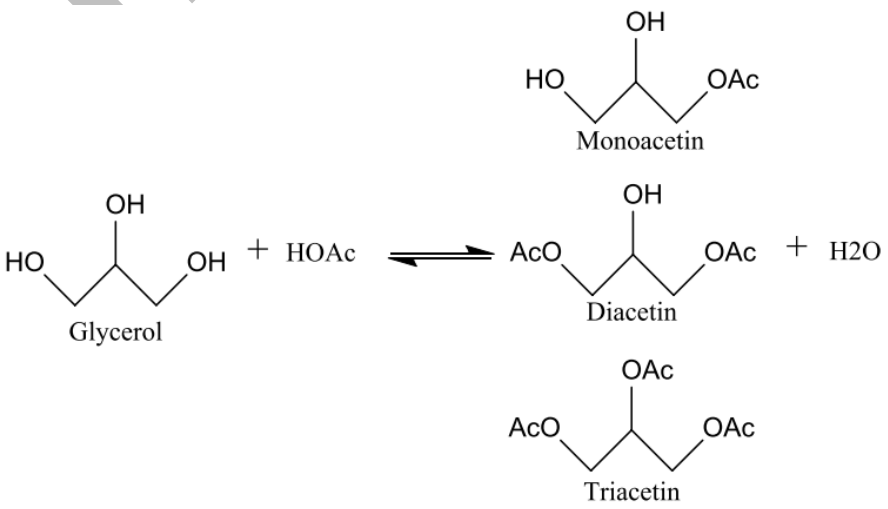


Figure 6. Chemical production of Triacetin [39]

Triacetin is characterized as a colorless, odorless and viscous liquid and is recognized as the smallest triacylglyceride [36]. It has a viscosity of 17.4 cP at 25 °C and a boiling point of 258 °C. Compared with other plasticizers such as Acetyl Triethyl Citrate (ATEC), Tributyl Citrate (TBC) and Acetyl Tributyl Citrate (ATBC), Triacetin demonstrates higher plasticization efficiency when blended with Eudragit L100-55 [40]. Rawat & Goswami [36] reported that Triacetin reduces both the melting point (T_m) and glass transition temperature (T_g) of polyvinyl alcohol (PVA), improving its processability. Johar et al. [39] also observed that the incorporation of Triacetin in polylactic acid (PLA) decreases tensile strength but improves elongation at break. This performance is primarily due to Triacetin's smaller molecular size, which enhances interactions with polymer chains and effectively reduces brittleness.

Table 2. Properties of Triacetin [27]

Plasticizer	Formula	Flash point (°C)	Kinematic viscosity (mm^2/s)	Melting point (°C)	Oxygen content (wt.%)	Enthalpy of vaporization (kJ/mol)
Triacetin	$C_9H_{14}O_6$	138	7.83	-78	49.5	84.3

Triacetin has strong market demand due to its wide applications as a food additive, emulsifier, plasticizer, stabilizer and in tobacco products, among others. A market report projected that the global Triacetin market would increase from USD 234.5 million to USD 309.9 million by 2022, reflecting a compound annual growth rate (CAGR) of 4.8% [27].

2.2.2 Acetyl Tributyl Citrate (ATBC)

Acetyl Tributyl Citrate (ATBC) is a citrate ester commonly classified as a non-phthalate plasticizer [41]. It has been used in food-contact materials, medical products, coatings, cosmetics and polymer formulations. Its chemical structure is shown in Figure 7. ATBC is widely used in food packaging, medical devices, cosmetics and toys. In cosmetics, it is applied in products for hair, nails and eyes. It is also commonly used in PVC products, coating formulations and blood bags [42]. A study by Lin et al. [43] further highlighted ATBC's suitability as a pharmaceutical excipient in drug delivery systems and coatings.

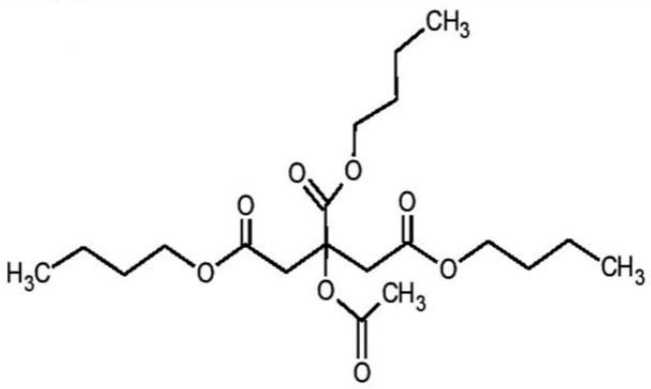


Figure 7. Chemical structure of Acetyl Tributyl Citrate (ATBC) [43]

A recent report projected that the global non-phthalate plasticizer market, including ATBC, will grow from approximately USD 3.1 billion in 2021 to around USD 3.9 billion by 2025 [41]. Koedthip et al. [42] reported that ATBC not only functions as a plasticizer for PLA but also acts as a compatibilizer within polymer blends, improving the dispersion of natural rubber in the P-PLA matrix. This enhances overall compatibility and dispersion, demonstrating that ATBC softens polymers while strengthening interfacial interactions, resulting in a more homogeneous and stable material.

Although previous studies have reported plasticizing and compatibilizing effects of ATBC in other polymer systems, these findings should not be directly extrapolated to recycled PET. Therefore, its interaction with recycled PET was evaluated specifically under the processing conditions used in the present study.

3. Methodology

3.1 PET Waste Preparation

In this study, polyethylene terephthalate (PET) obtained from mineral water and soft drink bottles was selected as the base material. PET is a thermoplastic polyester composed of repeating ethylene terephthalate units containing aromatic rings and ester linkages [26]. This molecular structure contributes to its high strength, toughness, chemical resistance and relatively high resistance to biodegradation.

The PET waste bottles were obtained from recycling centers located in Kuantan, Pahang. To ensure proper identification, only bottles marked with the PET recycling logo were selected. For consistency, bottles were carefully

sorted according to type, as mechanical and chemical properties can vary with brand and composition. In this study, white bottles with blue labels from the same brand were used exclusively, as shown in Figure 8(a).

All bottles were cleaned, separated from caps and labels and dried before processing. The PET bottles were air-dried at room temperature (25 ± 2 °C) for 24 h to reduce residual surface moisture before thermal processing. This step was intended to minimise the risk of moisture-induced hydrolytic degradation during thermal processing. The cleaned PET bottles were cut into flakes approximately 1–5 mm in size to facilitate more uniform heating [44]–[45]. The flakes were subsequently heated in a furnace (Thermo SCIENTIFIC) under ambient atmospheric conditions at a processing temperature of 300 °C for 3 hours to maintain a molten state, as illustrated in Figure 8(b). This temperature range is consistent with reported thermal parameters for melting PET waste, with an optimal melting condition of approximately 280–300 °C for about 2–3 hours [46], facilitating effective melting and processing prior to plasticizer incorporation. Following thermal processing, the selected plasticizer was gradually incorporated into the softened PET according to the formulations described in Section 3.2. It is acknowledged that PET can begin to undergo thermal degradation at those temperatures [47], which may lead to partial chain scission, cleavage of ester linkages and modification of ester functional groups, as well as the possible formation of additional carbonyl-containing species. Such structural changes may influence the interaction between PET and plasticizers. Therefore, FTIR analysis was performed to examine the chemical structure of the thermally treated PET and to evaluate its compatibility with Triacetin and ATBC plasticizers.



(a) (b)

Figure 8. PET waste preparation: (a) PET flakes after cleaning and cutting and (b) thermal processing of PET at 300 °C for 3 hours

3.2 Preparation of Plasticized PET

Triacetin with a purity of 99% and Acetyl Tributyl Citrate with a purity of 98% were supplied by Sigma-Aldrich. Triacetin was incorporated at 15, 30 and 40 wt.%, whereas ATBC was incorporated at 15 and 30 wt.%. A trial formulation containing 40 wt.% ATBC was prepared but excluded from subsequent FTIR analysis because a suitable intact specimen could not be obtained.

Following thermal processing, the plasticizer was gradually added to the softened PET and mixed using an overhead mechanical stirrer equipped with a suitable impeller at 60 rpm for 6 min to promote dispersion throughout the PET matrix. Only intact specimens were selected for subsequent ATR-FTIR analysis.

3.3 Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) is widely applied to detect the formation or disappearance of functional groups in polymers and to examine molecular interactions between polymer matrices and additives. In this study, FTIR was used as a primary analytical tool to evaluate the incorporation of plasticizers into the PET matrix and to identify changes in characteristic functional groups after modification. While FTIR provides valuable insight into chemical structure and intermolecular interactions, it primarily reflects molecular-level changes rather than direct material performance. Therefore, the present work focuses on spectroscopic evaluation as an initial step towards understanding the compatibility between recycled PET and the selected plasticizers.

In this study, Fourier Transform-Attenuated Total Reflectance Infrared Spectroscopy (FT-ATR) was conducted using a Nicolet iS50 (Thermo Fisher Scientific) at the Faculty of Chemical and Process Technology Laboratory, Universiti Malaysia Pahang Al-Sultan Abdullah. The cleaned PET bottles were cut into flakes measuring approximately 1–5 mm and heated in the furnace at 300 °C for 3 hours. After cooling to room temperature, samples were ground into pieces to obtain specimens suitable for ATR-FTIR analysis as shown in Figure 9. Grinding was used only to improve contact between the sample and the ATR crystal. Nevertheless, possible effects of sample preparation on spectral intensity cannot be completely excluded and direct thin-film preparation should be considered in future studies.



Figure 9. Ground PET specimens prepared for ATR-FTIR analysis

The analysed formulations comprised unmodified PET, PET/Triacetin at 15, 30 and 40 wt.% and PET/ATBC at 15 and 30 wt.%. Each specimen was scanned three times under identical instrumental conditions. The repeated spectra were evaluated for consistency in peak position and overall spectral profile. These measurements represent instrumental repeatability rather than independent sample replication.

3.4 Preparation of Plasticized PET

The preparation process in this study as shown in Figure 10 begins with thoroughly cleaning the PET plastic bottles to remove any dirt, labels or contaminants that could affect the quality of the final material. Once cleaned, the bottles were cut into small pieces measuring approximately 1–5 mm to ensure faster and more uniform melting during processing. These PET fragments were then placed in a furnace and heated at 300 °C for a duration of three hours, allowing the polymer to fully melt and reach a workable viscous state. After complete melting, ATBC was incorporated at 15 and 30 wt.%, whereas Triacetin was incorporated at 15, 30 and 40 wt.%. A trial formulation containing 40 wt.% ATBC was excluded from subsequent FTIR analysis because a suitable intact specimen could not be obtained. The mixture was subsequently blended using an overhead mechanical stirrer equipped with a suitable impeller at a rotational speed of 60 rpm for 6 min to promote dispersion of the plasticizer throughout the molten PET [48]. The blended materials were allowed to cool and solidify overnight at room temperature. Once fully cooled and solidified, representative samples were collected and prepared for FTIR analysis to examine the spectral changes associated with the incorporation of plasticizers into the PET matrix.

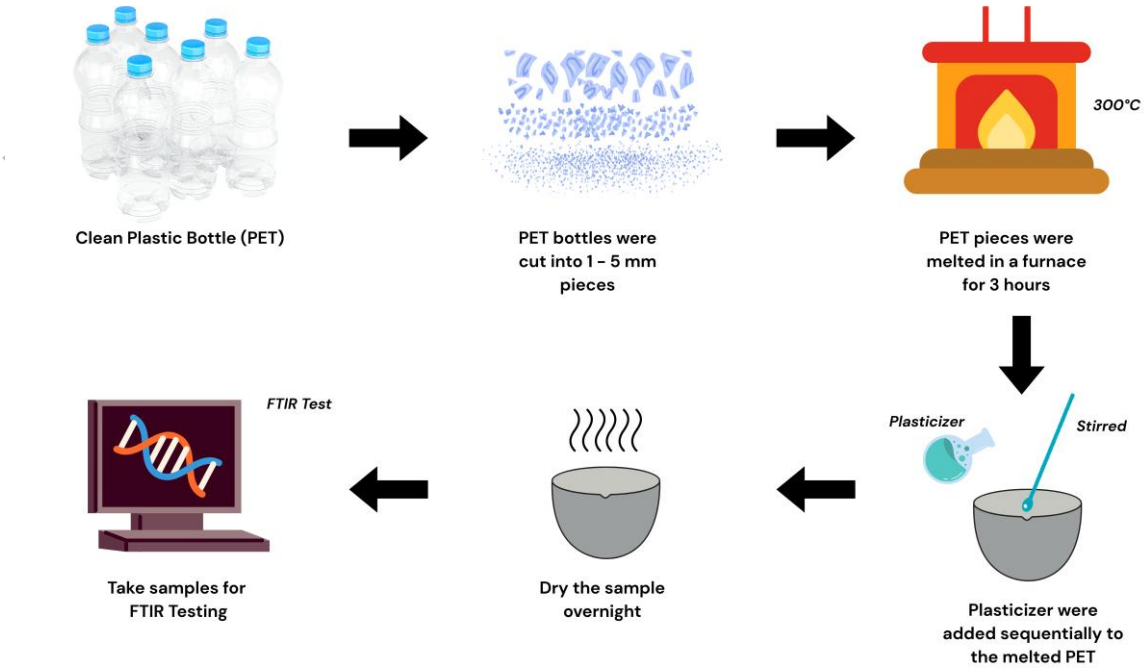


Figure 10. Experimental procedure for preparing thermally processed and plasticizer-modified recycled PET specimens

3.5 Semi-Quantitative Peak Ratio Analysis

A semi-quantitative FTIR peak ratio analysis was performed by normalizing the intensity of selected absorption peaks with respect to a reference peak that remains relatively unchanged across all samples [49]–[50]. The peak ratio was calculated using Equation 1.

$$Peak\ Ratio = \frac{Intensity\ of\ target\ peak}{Intensity\ of\ reference\ peak} \quad (1)$$

Prior to analysis, all spectra were baseline-corrected and smoothed to minimize noise and ensure consistency in peak identification. The absorption band at 1410 cm^{-1} was selected as the reference peak because its position and intensity remained comparatively unchanged across all formulations. The target peaks corresponding to C=O, C–O and C–C–O vibrations were evaluated at approximately 1719, 1090 and 1240 cm^{-1}, respectively. Peak heights were extracted after baseline correction using identical processing parameters in OriginLab. The selected peaks were chosen based on their sensitivity to structural changes and their relevance to ester functionalities in both PET and the plasticizers.

4. Results and Discussions

4.1 Spectroscopic Analysis of PET

Thermal exposure of PET at elevated temperatures may induce partial degradation of the polymer backbone through ester bond cleavage and oxidation reactions. Such structural modifications can influence the interaction between PET and plasticizers, which is reflected in the FTIR spectral characteristics observed in this study.

The FTIR spectrum of pure PET (red curve) displays characteristic absorption bands consistent with its chemical structure. A strong peak at 1708 cm^{-1} corresponds to the carbonyl (C=O) stretching vibration of the ester group, the dominant functional group in PET. Bands in the range of 1245–1100 cm^{-1} are attributed to C–C–O stretching vibrations within the ester linkage, while peaks near 1400–1500 cm^{-1} are associated with C–H bending from the aromatic ring. These distinct peaks confirm the polymer backbone of PET and provide a reliable reference for assessing the effect of plasticizer incorporation. Furthermore, the absence of a prominent broad O–H band between 3200 and 3500 cm^{-1} suggests limited detectable moisture or hydroxyl-containing species under the measurement conditions.

These spectral features are consistent with published literature [29]–[30] and validate the quality of the PET sample prior to modification. The strong ester and aromatic peaks reflect PET's high durability and chemical resistance, which explain its widespread industrial use but also its resistance to biodegradation. Establishing this baseline is crucial, as any observed shifts in the C=O stretching band, intensity changes in the C–C–O and aromatic regions or the appearance of new absorption peaks in modified samples may serve as direct indicators of interactions between PET and the plasticizers (Triacetin or ATBC). Such changes may indicate the incorporation of the additives and alterations in the local molecular environment of PET. However, changes in polymer chain mobility cannot be confirmed by FTIR alone and require complementary thermal or rheological analysis. The FTIR analysis results for the PET samples in this study are presented in Figure 11.

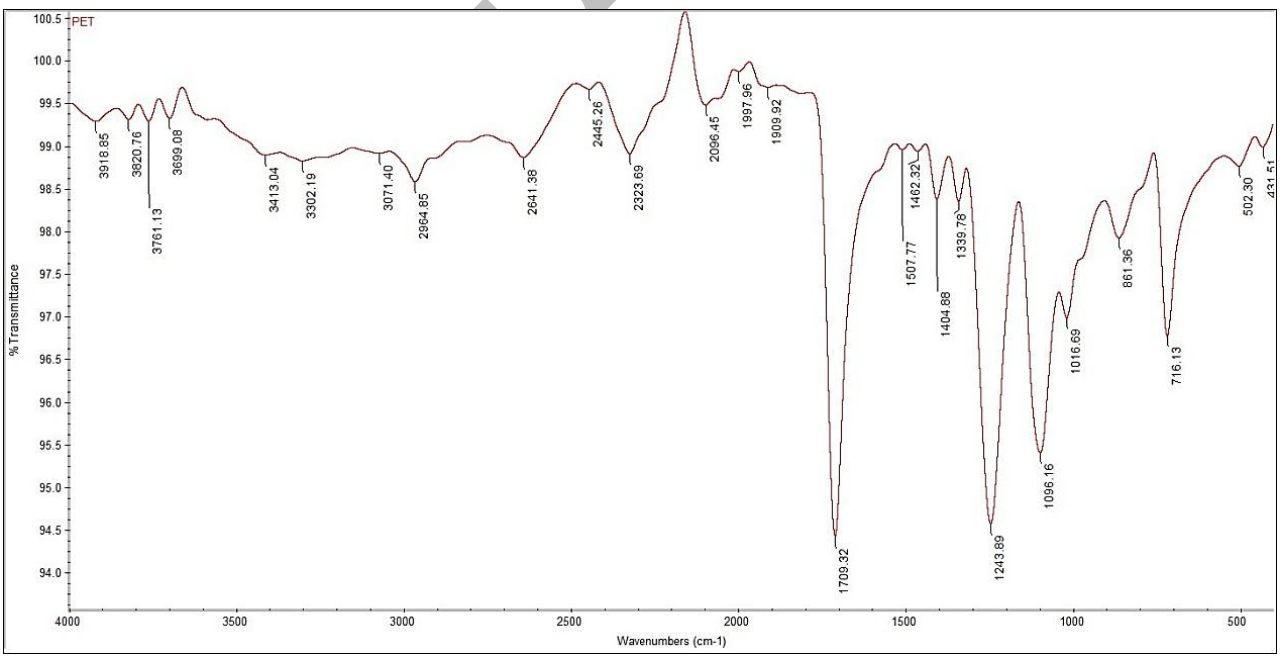
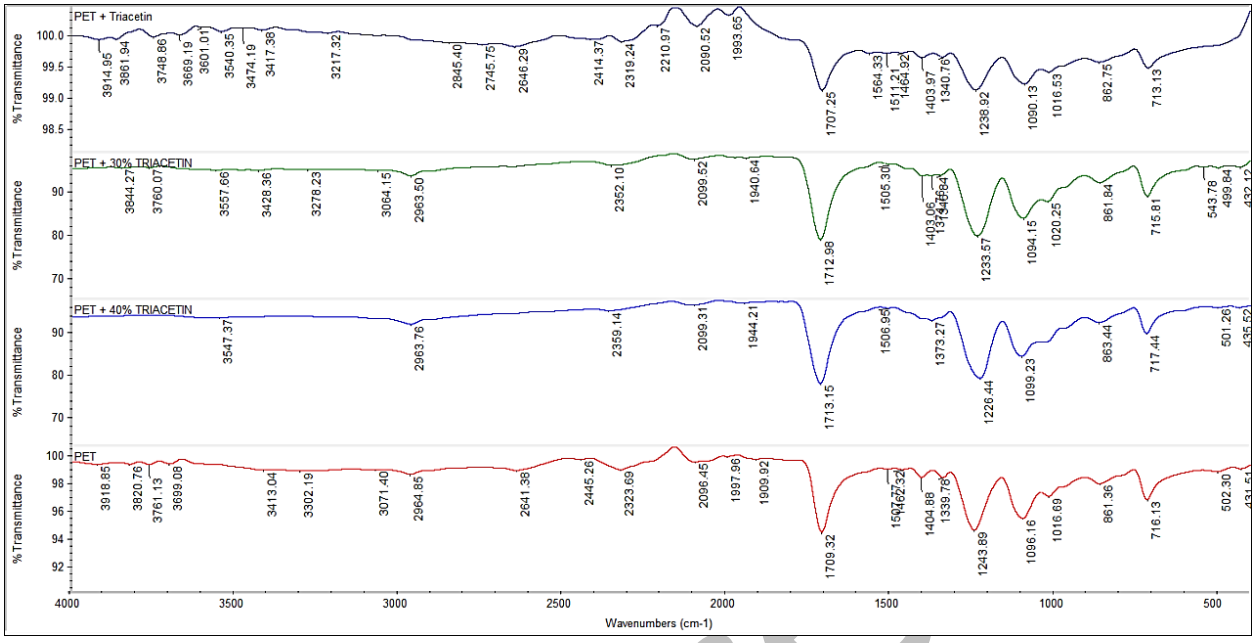


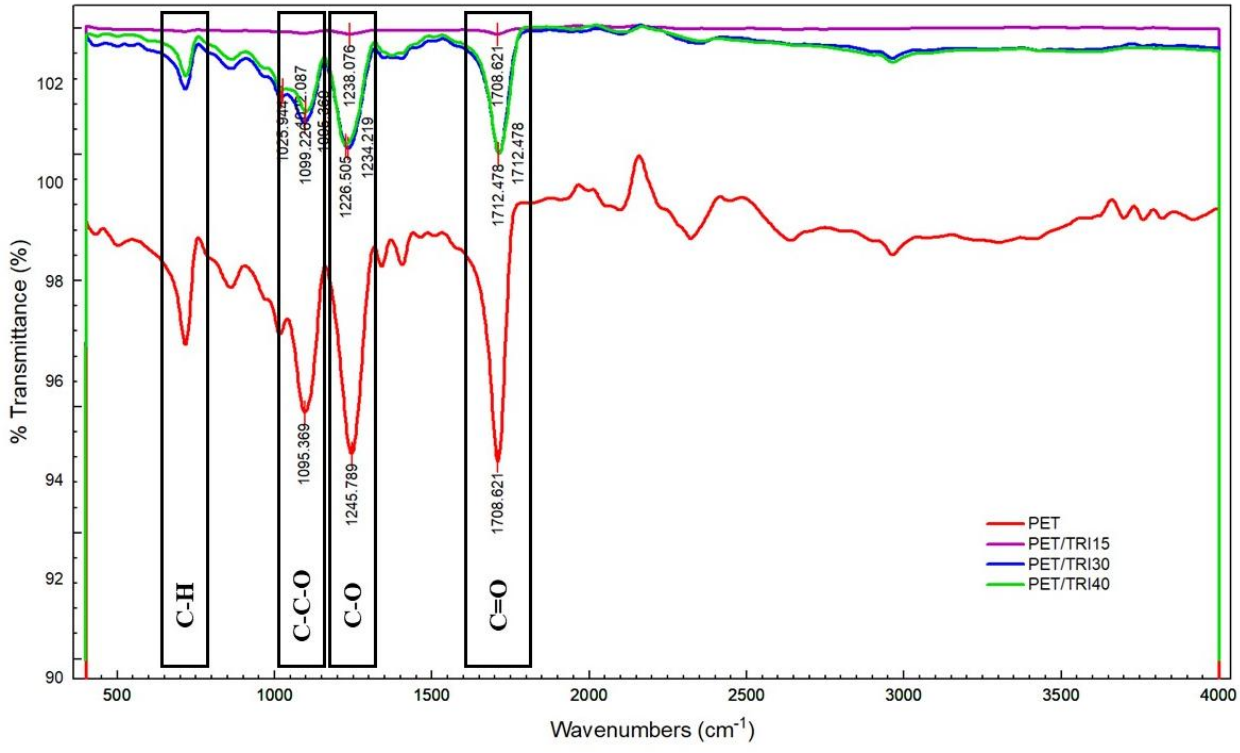
Figure 11. FTIR analysis for PET sample

4.2 PET with Triacetin

Fourier Transform Infrared (FTIR) analysis was conducted to examine the modification of PET waste with Triacetin, as shown in Figure 12(a). The characteristic absorption peaks of PET and Triacetin, analyzed using OriginLab software, are presented in Figure 12(b), highlighting the functional groups associated with their molecular structures.



(a)



(b)

Figure 12. (a) FTIR analysis for PET with 15%, 30% and 40% of Triacetin (b) Peak comparisons

When PET was blended with 15 wt.% Triacetin (PET/TRI15, purple curve), noticeable spectral changes were observed relative to unmodified PET. The carbonyl band near 1708 cm^{-1} became slightly broadened and shifted, suggesting possible non-covalent interactions, including dipole–dipole interactions, between the carbonyl-containing groups of Triacetin and the ester groups of PET. In addition, increased intensity in the C–C–O stretching region between 1100 and 1250 cm^{-1} reflected the contribution of Triacetin-related ester groups. These observations support the physical incorporation of Triacetin and changes in the local spectral environment of PET at this concentration.

For 30 wt.% Triacetin (PET/TRI30, blue curve), more pronounced spectral changes were observed. The carbonyl stretching band shifted to approximately 1712 cm^{-1} and increased in intensity. The C–H stretching bands between 2850

and 2950 cm^{-1} also became more distinct, reflecting the contribution of aliphatic groups from Triacetin. Increased intensity in the C–C–O region further supported the incorporation of Triacetin into the thermally processed PET system. These changes indicate a greater concentration-dependent spectral response at 30 wt.%. However, changes in polymer chain mobility or glass transition temperature were not directly measured in this study.

At 40 wt.% Triacetin (PET/TRI40, green curve), further changes were observed in the carbonyl, C–C–O and aliphatic C–H regions. The carbonyl band shifted to approximately 1712–1714 cm^{-1} and showed additional broadening, while the C–C–O and C–H bands increased in intensity. These findings indicate a further contribution of Triacetin-related functional groups at the highest concentration investigated. However, the FTIR results alone cannot confirm oversaturation, phase separation, plasticizer leaching, reduced mechanical strength or changes in processability.

Across all Triacetin concentrations, no new characteristic absorption bands were detected. This suggests that the observed spectral changes were predominantly associated with physical interactions rather than the formation of new covalent functional groups. Carbonyl broadening and increased C–C–O and C–H intensities were consistent with concentration-dependent incorporation of Triacetin. The effects of these changes on flexibility, processability, thermal behaviour and mechanical performance require confirmation through complementary thermal, rheological and mechanical testing.

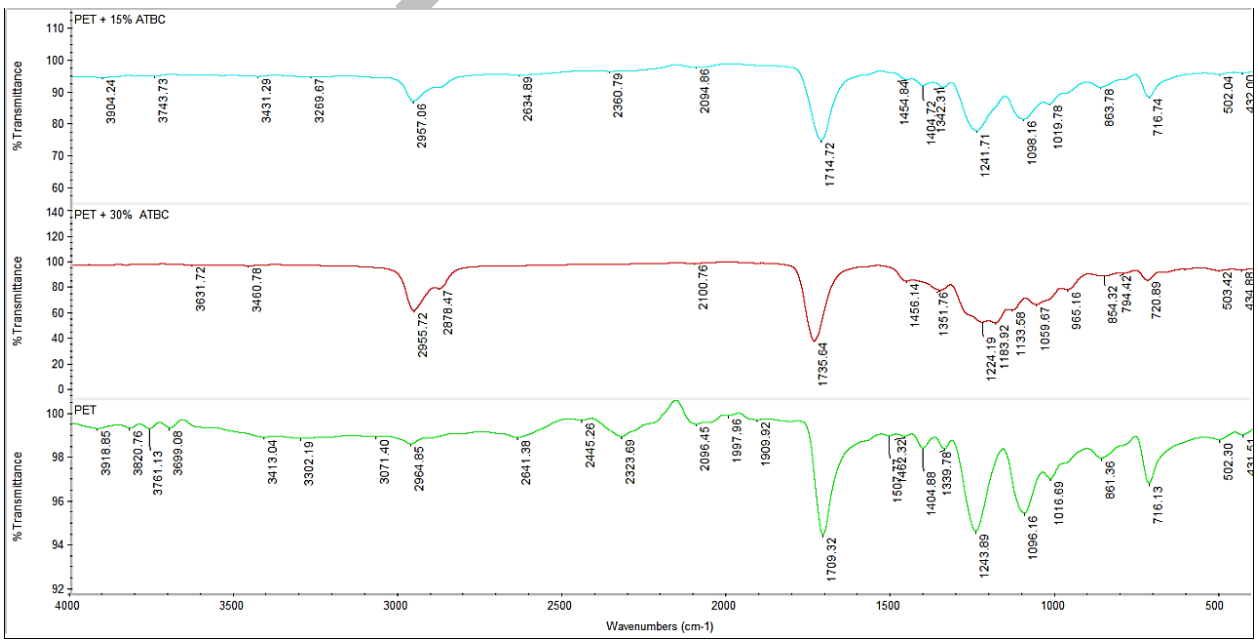
4.3 PET with ATBC

Fourier Transform Infrared (FTIR) analysis was carried out to evaluate the modification of PET waste with Acetyl Tributyl Citrate (ATBC), as illustrated in Figure 13(a). The characteristic absorption peaks of PET and ATBC, analyzed using OriginLab software, are shown in Figure 13(b), highlighting the functional groups associated with their molecular structures.

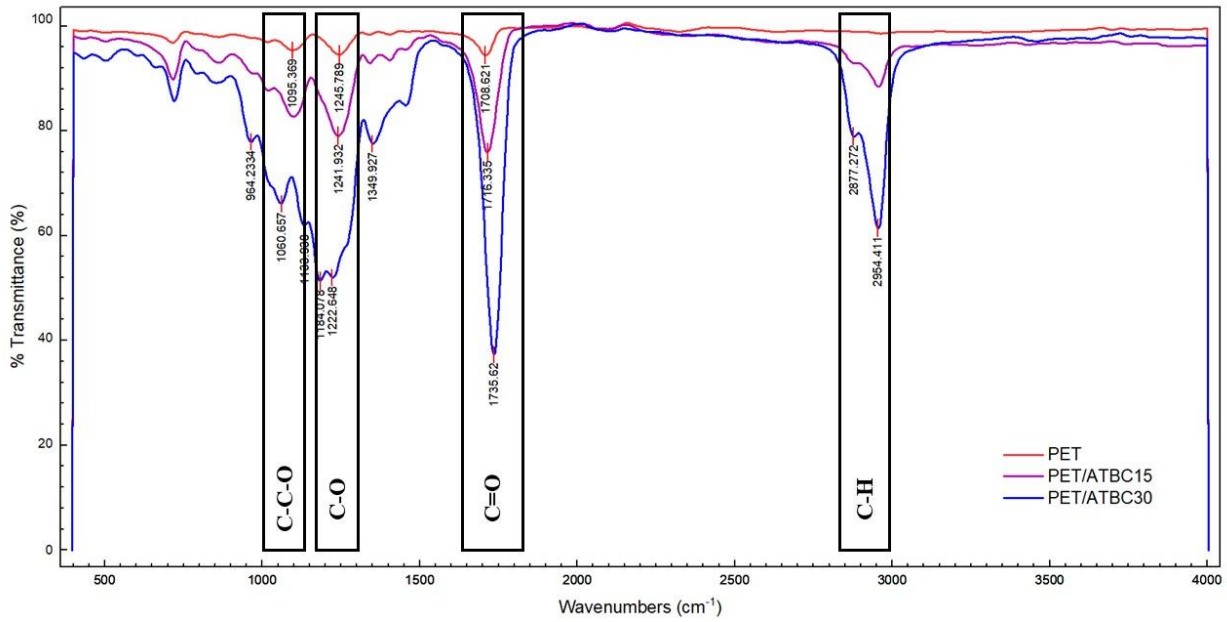
The PET used in this study underwent thermal treatment at 300 °C prior to modification. Thermal exposure at this temperature can induce partial degradation of PET through the chain scission and alteration of ester functional groups. These structural changes may affect the intermolecular interactions between PET and the incorporated plasticizers. The FTIR results therefore provide useful insight into the chemical structure of thermally treated PET and the manner in which Triacetin and ATBC interact with the modified polymer matrix.

At 15 wt.% ATBC (PET/ATBC15, purple curve), moderate spectral changes were observed relative to unmodified PET. The carbonyl region between approximately 1708 and 1735 cm^{-1} showed a slight increase in intensity, reflecting the contribution of ATBC ester carbonyl groups. The C–O stretching bands between 1100 and 1240 cm^{-1} also increased, while the aliphatic C–H stretching bands near 2954 and 2877 cm^{-1} became more pronounced. No new characteristic absorption bands were detected. These findings support the physical incorporation of ATBC and changes in the local spectral environment of PET.

For 30 wt.% ATBC (PET/ATBC30, blue curve), the carbonyl, C–O and aliphatic C–H bands showed more pronounced intensity changes. The stronger carbonyl band near 1735 cm^{-1} reflected the greater contribution of ATBC-related ester groups at the higher concentration. The C–O bands between approximately 1095 and 1240 cm^{-1} also intensified, while the C–H stretching bands became more prominent. These results indicate a stronger concentration-dependent spectral response at 30 wt.% ATBC. However, changes in crystallinity, chain mobility, softness, ductility or mechanical performance cannot be confirmed from FTIR data alone.



(a)



(b)

Figure 13. (a) FTIR analysis for PET with 15% and 30% of ATBC (b) Peak comparisons

Across both ATBC concentrations, the C–C–O stretching bands increased in intensity and broadened, supporting the contribution of ATBC-related ester groups. The present FTIR findings demonstrate concentration-dependent spectral changes after ATBC incorporation. However, the suitability of the 15 and 30 wt.% formulations for structural or non-structural applications requires additional thermal, rheological, mechanical, migration and polymer concrete performance testing.

4.4 Semi-Quantitative Peak Ratio Analysis

To further evaluate the spectral changes associated with the interactions between PET and the selected plasticizers, Triacetin and ATBC, a semi-quantitative FTIR analysis was performed by normalizing the intensity of selected functional groups against a stable reference peak associated with the PET backbone. Table 3 demonstrates the semi-quantitative FTIR peak ratio analysis of PET modified with Triacetin and ATBC. The normalized peak ratios provide a semi-quantitative comparison of concentration-dependent changes in selected absorption bands. These values indicate relative spectral variations but do not independently establish interaction strength or statistically significant differences. Values represent repeated scans of the same prepared specimen and therefore reflect instrumental repeatability rather than inter-sample variability.

Table 3. Semi-Quantitative Peak Ratio Analysis of Triacetin and ATBC as PET Plasticizers

	C=O	C-O	C-C-O
PET (Reference peak)	1.00	1.00	1.00
PET/TRI15	1.10	1.08	1.06
PET/TRI30	1.20	1.18	1.12
PET/TRI40	1.25	1.22	1.15
PET/ATBC15	1.15	1.12	1.10
PET/ATBC30	1.35	1.30	1.25

Note: C=O – Carbonyl group, C-O – Carbon-oxygen single bond, C-C-O – Carbon-carbon-oxygen skeletal

The values in Table 3 represent the mean normalized peak ratios obtained from three repeated scans of the same prepared specimen. Because the scans were not obtained from independently prepared specimens, the data reflect instrumental repeatability rather than inter-sample variability and no inferential statistical comparison was performed. The normalized peak ratios provide a semi-quantitative comparison of concentration-dependent changes in selected absorption bands. These values represent relative spectral responses and should not be interpreted as direct measurements of interaction strength, plasticization efficiency or statistically significant differences. As the Triacetin concentration increased, a gradual increase in the C=O, C–O and C–C–O ratios was observed. This trend indicates an increasing spectral contribution from Triacetin-related ester groups within the thermally processed PET system. The smaller increase between 30 and 40 wt.% Triacetin indicates a non-linear concentration-dependent spectral response. However, the present

FTIR data do not directly demonstrate reduced plasticization efficiency, saturation, phase segregation or limited miscibility.

For the PET/ATBC system, the normalized peak ratios were higher than those obtained for PET/Triacetin at equivalent nominal concentrations. These higher values indicate a greater spectral contribution from ATBC-related ester groups and corresponding changes in the local chemical environment. Because ATBC contains several ester functionalities, part of the increase may reflect compositional differences between the plasticizers rather than stronger plasticization alone. Therefore, the higher ATBC peak ratios should be interpreted as a greater normalized spectral response and not as conclusive evidence of superior compatibility, interaction efficiency, plasticization capability or long-term performance. At comparable concentrations, ATBC produced higher normalized peak ratios than Triacetin, indicating a greater concentration-dependent FTIR response. However, this difference does not independently establish superior plasticization efficiency or material performance.

4.5 Comparison of Triacetin and ATBC

Both Triacetin and ATBC act as external plasticizers for PET, but their effects differ due to variations in their molecular structures, as summarized in Table 4.

Table 4. Summary Comparison of Triacetin and ATBC as PET Plasticizers

Aspect	(PET/TRI)	(PET/ATBC)	Interpretation within this study
Carbonyl region	Slight shift and broadening around 1710–1714 cm^{-1}	More pronounced intensity increase in the carbonyl region	Both plasticizers altered the local ester-related spectral environment
C–C–O region	Increased intensity with concentration	Greater intensity increase at 15 and 30 wt.%	Indicates concentration-dependent contribution from ester-containing plasticizers
C–H region	Increased aliphatic C–H absorption	More pronounced aliphatic C–H peaks	Reflects incorporation of aliphatic groups from the plasticizers
New characteristic bands	No new characteristic bands detected	No new characteristic bands detected	Suggests predominantly physical incorporation without formation of major new covalent functional groups
Peak-ratio response	Gradual increase with loading	Higher normalized ratios at equivalent loading	Shows different concentration-dependent spectral responses; does not alone prove superior plasticization
Study limitation	Long-term stability, migration and mechanical performance not evaluated	Long-term stability, migration and mechanical performance not evaluated	Requires complementary thermal, mechanical, rheological, migration and durability tests

For PET blended with Triacetin, moderate shifts and broadening were observed in the carbonyl region, together with increased C–C–O and aliphatic C–H absorption. These changes support the physical incorporation of Triacetin and alterations in the local ester-related spectral environment without evidence of the formation of new characteristic covalent functional groups. PET modified with ATBC exhibited more pronounced intensity changes in the carbonyl, C–O, C–C–O and aliphatic C–H regions, particularly at 30 wt.%. These differences indicate a greater FTIR response associated with ATBC-related ester and aliphatic groups at comparable concentrations. However, long-term flexibility, resistance to embrittlement, migration behaviour and durability were not evaluated in this study.

The observed peak shifts and intensity changes indicate alterations in the local vibrational environment of ester and aliphatic groups following plasticizer incorporation. These spectral changes are consistent with predominantly non-covalent interactions. Although such interactions may influence free volume and molecular mobility, their effects on flexibility, processability, crystallinity and mechanical performance were not directly measured. The FTIR results suggest that both Triacetin and ATBC interact physically with thermally processed recycled PET without forming major new covalent functional groups. The present findings therefore provide preliminary molecular-level evidence of plasticizer incorporation. Complementary thermal analysis, such as DSC or TGA, together with rheological, mechanical, migration, morphological and durability testing, is required to determine the practical performance of the modified PET systems.

4. Conclusions

This study comparatively investigated the molecular-level interactions between recycled PET and two selected non-phthalate plasticizers, Triacetin and Acetyl Tributyl Citrate (ATBC), at different concentrations using FTIR spectroscopy following thermal processing at approximately 300 °C. The FTIR results showed concentration-dependent changes in the carbonyl, C–O, C–C–O and C–H absorption bands after the incorporation of Triacetin and ATBC. The absence of new characteristic absorption bands suggests that the observed changes were predominantly associated with physical intermolecular interactions rather than the formation of new covalent functional groups. Semi-quantitative peak-ratio analysis further demonstrated relative variations in selected absorption bands with increasing plasticizer concentration.

UMP Press

At 30 wt.% plasticizer loading, the normalized C=O, C–O and C–C–O peak ratios were 1.20, 1.18 and 1.12 for Triacetin-modified PET, compared with 1.35, 1.30 and 1.25 for ATBC-modified PET, respectively. These results support the incorporation of both plasticizers into the thermally processed PET system and provide preliminary molecular-level evidence of differences in their spectral responses.

However, FTIR analysis alone does not directly determine polymer chain mobility, plasticization efficiency, long-term stability, migration resistance, mechanical performance or durability. Therefore, the present findings should be interpreted as a preliminary spectroscopic assessment of PET–plasticizer interactions rather than confirmation of practical performance in polymer concrete. Future research should correlate the observed spectral changes with thermal, rheological, mechanical, microstructural and durability properties of the modified PET. In particular, workability, strength development, long-term ageing, plasticizer migration, alkaline resistance and performance within polymer concrete systems should be evaluated under service-relevant conditions. These investigations are necessary to determine the practical suitability of plasticized recycled PET as a potential binder or matrix component in construction composites.

Acknowledgements
The authors would like to thank the Faculty of Civil Engineering Technology and Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah for providing the necessary resources and equipment for this research.

Funding
This work was supported by a research grant from Universiti Malaysia Pahang Al-Sultan Abdullah allocated under the internal grant RDU230301.

Declaration of Competing Interests
The authors declare no conflicts of interest.

CRediT Author Contribution Statement
S. I. Mohd Nazri (Methodology; Data curation; Writing - original draft; Resources)
M. F. Mohamad Borhan (Methodology; Data curation; Writing - original draft; Resources)
N. F. Ariffin (Conceptualization; Validation; Writing - review & editing; Supervision)
A. N. Salim Salmi (Methodology; Data curation)
S. M. Syed Mohsin (Resources; Funding acquisition)
G. A. Jokhio (Conceptualization)
M. A. Ismail (Conceptualization)

Availability of Data and Materials
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement
This study did not involve human participants or animal subjects. Ethical approval was therefore not required for this research.

Generative Artificial Intelligence Disclosure
AI-based tools were used solely for language editing and grammar refinement. No AI content generation or data interpretation was performed. All intellectual contributions are original and solely attributable to the authors.

References
[1] S. S. Shkur, A. A. Mohammed, S. A. Ahmad, and H. F. Mahmood, "Effects of Using Natural Fibers on the Fresh and Mechanical Properties of Concrete: A Comprehensive Review," *Smart and Green Materials*, vol. 2, no. 2, pp. 112–128, 2025. https://doi.org/10.70028/SGM.V2I2.47
[2] N. Syahira, I. A. Hassan, D. Zulaika, A. Hasbollah, N. Mohd Muztaza, and Y. Yuliana, "Peat Soil Stabilizer Using Plastic Waste," *Smart and Green Materials*, vol. 1, no. 1, pp. 44–56, 2024. https://doi.org/10.70028/SGM.V1I1.4
[3] S. Waysal, Y. D. Patil, B. Z. Dholkiya, and A. M. Bhoi, "Employing copper slag and pet polymer in self-compacting concrete," *Materials Today Proceedings*, vol. 93, pp. 515–521, 2023. https://doi.org/10.1016/J.MATPR.2023.08.378
[4] S. I. Mohd Nazri, N. F. Ariffin, and M. F. Mohamad Borhan, "Evolutionary process and mechanical properties of polymers: A comprehensive review," *Challenge Journal of Concrete Research Letters*, vol. 16, no. 4, pp. 225–242, 2025. https://doi.org/10.20528/cjcrl.2025.04.005
[5] T. Massoud and J. Dsilva, "Closing the PET plastic recycling loop: A sustainable transformation from plastic to fiber," *Next Sustainability*, vol. 6, p. 100095, 2025. https://doi.org/10.1016/J.NXSUST.2024.100095
[6] T. M. Chandramouli Swamy, S. V. Nagarathna, P. V. Reddy, and A. S. Nayak, "Efficient biodegradation of Polyethylene terephthalate (PET) plastic by Gordonia sp. CN2K isolated from plastic contaminated environment,"

In-Press

Ecotoxicology and Environmental Safety, vol. 281, p. 116635, 2024. https://doi.org/10.1016/J.ECOENV.2024.116635

[7] Y. H. V. Soong, M. J. Sobkowicz, and D. Xie, "Recent Advances in Biological Recycling of Polyethylene Terephthalate (PET) Plastic Wastes," *Bioengineering*, vol. 9, no. 3, 2022. https://doi.org/10.3390/bioengineering9030098

[8] R. M. Packieya Eswari, K. Sherjin, K. Thiruvasagam, and S. Nandha Kumar, "Flexural Behavior of Non-Biodegradable Plastic PET Bottles as a Part of Reinforcement in Beams," *Journal of Rehabilitation in Civil Engineering*, vol. 14, no. 1, p. 2181, 2026. https://doi.org/10.22075/JRCE.2025.35530.2181

[9] A. R. Rahimi and J. M. Garciá, "Chemical recycling of waste plastics for new materials production," *Nature Reviews Chemistry*, vol. 1, 2017. https://doi.org/10.1038/S41570-017-0046

[10] Z. Jia, L. Gao, L. Qin, and J. Yin, "Chemical recycling of PET to value-added products," *RSC Sustainability*, vol. 1, no. 9, pp. 2135–2147, 2023. https://doi.org/10.1039/D3SU00311F

[11] C. Y. Wang, H. Y. Chu, and C. C. Wang, "Converting waste PET plastics to high value-added MOFs-based functional materials: A state of the art review," *Coordination Chemistry Reviews*, vol. 518, p. 216106, 2024. https://doi.org/10.1016/J.CCR.2024.216106

[12] Y. Mouna, B. Irfan, M. S. Rahman, and M. Batikha, "A statistical-experimental study to investigate the optimal parameters of fibres made from waste PET bottles for strengthening concrete," *Construction and Building Materials*, vol. 420, p. 135613, 2024. https://doi.org/10.1016/J.CONBUILDMAT.2024.135613

[13] M. J. Islam, M. S. Meherier, and A. K. M. R. Islam, "Effects of waste PET as coarse aggregate on the fresh and harden properties of concrete," *Construction and Building Materials*, vol. 125, pp. 946–951, 2016. https://doi.org/10.1016/J.CONBUILDMAT.2016.08.128

[14] S. Sarwar, S. R. Molla, S. Das, L. Tammim, F. F. Ahmed, and S. Akter, "Algal deterioration of PET (polyethylene terephthalate) plastic bottle in combination with physical and chemical pretreatments: A macrocosm study," *Environmental and Sustainability Indicators*, vol. 21, 2024. https://doi.org/10.1016/j.indic.2023.100329

[15] D. A. Silva, A. M. Betioli, P. J. P. Gleize, H. R. Roman, L. A. Gómez, and J. L. D. Ribeiro, "Degradation of recycled PET fibers in Portland cement-based materials," *Cement and Concrete Research*, vol. 35, no. 9, pp. 1741–1746, 2005. https://doi.org/10.1016/j.cemconres.2004.10.040

[16] Z. H. Lee, S. C. Paul, S. Y. Kong, S. Susilawati, and X. Yang, "Modification of Waste Aggregate PET for Improving the Concrete Properties," *Advances in Civil Engineering*, vol. 2019, no. 1, p. 6942052, 2019. https://doi.org/10.1155/2019/6942052

[17] M. Nodehi, "Epoxy, polyester and vinyl ester based polymer concrete: a review," *Innovative Infrastructure Solutions*, vol. 7, no. 1, 2022. https://doi.org/10.1007/s41062-021-00661-3

[18] K. Grigoriadis, J. Bañuls-Ciscar, A. Caverzan, P. Negro, C. Senaldi, and G. Ceccone, "Use of irradiated PET plastic waste for partially replacing cement in concrete?," *Waste Management*, vol. 170, pp. 193–203, 2023. https://doi.org/10.1016/j.wasman.2023.08.012

[19] M. K. Askar, Y. S. S. Al-Kamaki, and A. Hassan, "Utilizing Polyethylene Terephthalate PET in Concrete: A Review," *Polymers*, vol. 15, no. 15, 2023. https://doi.org/10.3390/POLYM15153320

[20] M. E. Kangavar, W. Lokuge, A. Manalo, W. Karunasena, and T. Ozbakkaloglu, "Development of sustainable concrete using recycled polyethylene terephthalate (PET) granules as fine aggregate," *Developments in the Built Environment*, vol. 15, p. 100192, 2023. https://doi.org/10.1016/J.DIBE.2023.100192

[21] S. M. D. V. Suraweera and S. De Silva, "Effect of Recycled Polyethylene Terephthalate (PET) fibres on fresh and hardened properties of concrete: a review," *International Journal of Sustainable Engineering*, vol. 16, no. 1, pp. 269–284, 2023. https://doi.org/10.1080/19397038.2023.2257735

[22] A. D. Almutairi *et al.*, "Comprehensive investigation of the mechanical performance and evaluate the environmental impact of Epoxy and Polyester polymer concrete," *Case Studies in Construction Materials*, p. e04195, 2024. https://doi.org/10.1016/J.CSCM.2024.E04195

[23] T. Tam Nguyen and K. Edalati, "Efficient photoreforming of plastic waste using a high-entropy oxide catalyst," *Journal of Catalysis*, vol. 440, p. 115808, 2024. https://doi.org/10.1016/j.jcat.2024.115808

[24] M. Babaei, M. Jalilian, and K. Shahbaz, "Chemical recycling of Polyethylene terephthalate: A mini-review," *Journal of Environmental Chemical Engineering*, vol. 12, no. 3, p. 112507, 2024. https://doi.org/10.1016/J.JECE.2024.112507

[25] S. A. N. A. Zuber, A. Rusli, and H. Ismail, "Effectiveness of triacetin and triethyl citrate as plasticizer in polyvinyl alcohol," *Materials Today Proceedings*, vol. 17, pp. 560–567, 2019. https://doi.org/10.1016/J.MATPR.2019.06.335

[26] M. Maiza, M. T. Benaniba, and V. Massardier-Nageotte, "Plasticizing effects of citrate esters on properties of poly(lactic acid)," *Journal of Polymer Engineering*, vol. 36, no. 4, pp. 371–380, 2016. https://doi.org/10.1515/polyeng-2015-0140

[27] N. Gama, R. Santos, B. Godinho, R. Silva, and A. Ferreira, "Triacetin as a Secondary PVC Plasticizer," *Journal of Polymers and the Environment*, vol. 27, no. 6, pp. 1294–1301, 2019. https://doi.org/10.1007/S10924-019-01432-Z

[28] E. Bugnicourt, P. Cinelli, A. Lazzeri, and V. Alvarez, "Polyhydroxyalkanoate (PHA): Review of synthesis, characteristics, processing and potential applications in packaging," *Express Polymer Letters*, vol. 8, no. 11, pp. 791–808, 2014. https://doi.org/10.3144/expresspolymlett.2014.82

[29] T. Ren *et al.*, "Recycling and high-value utilization of polyethylene terephthalate wastes: A review," *Environmental Research*, vol. 249, 2024. https://doi.org/10.1016/j.envres.2024.118428

UMP Press

[30] L. Umdagas, R. Orozco, K. Heeley, W. Thom, and B. Al-Duri, "Advances in chemical recycling of polyethylene terephthalate (PET) via hydrolysis: A comprehensive review," *Polymer Degradation and Stability*, vol. 234, 2025. https://doi.org/10.1016/j.polymdegradstab.2025.111246

[31] V. Dhaka *et al.*, "Occurrence, toxicity and remediation of polyethylene terephthalate plastics. A review," *Environmental Chemistry Letters*, vol. 20, no. 3, pp. 1777–1800, 2022. https://doi.org/10.1007/S10311-021-01384-8

[32] Z. Wang, Z. H. Phua, W. P. Chan, and G. Lisak, "Evaluating fresh and hardened properties of mortar composite with different types of modified polyethylene terephthalate (PET) materials as additives: Modification effects, surface properties, shape factors," *Chemosphere*, vol. 367, p. 143567, 2024. https://doi.org/10.1016/J.CHEMOSPHERE.2024.143567

[33] A. Sheel and D. Pant, "Chemical Depolymerization of PET Bottles via Glycolysis," *Recycling of Polyethylene Terephthalate Bottles*, pp. 61–84, 2019. https://doi.org/10.1016/B978-0-12-811361-5.00004-3

[34] H. Jeon *et al.*, "Identification and quantification of acetyl tributyl citrate (ATBC) metabolites using human liver microsomes and human urine," *Chemosphere*, vol. 363, p. 142840, 2024. https://doi.org/10.1016/J.CHEMOSPHERE.2024.142840

[35] R. Erdmann, S. Kabasci, and H. P. Heim, "Thermal Properties of Plasticized Cellulose Acetate and Its β-Relaxation Phenomenon," *Polymers*, vol. 13, no. 9, p. 1356, 2021. https://doi.org/10.3390/POLYM13091356

[36] S. Rawat and S. Goswami, "Development of a Biodegradable Ternary Blend of Poly(vinyl alcohol) and Polyhydroxybutyrate Functionalized with Triacetin for Agricultural Mulch Applications," *ACS Omega 2024*, no. 9, pp. 30169–30182, 2024. https://doi.org/10.1021/acsomega.3c10027

[37] M. J. Quinn and D. Ziolkowski, "Wildlife Toxicity Assessment for Triacetin," *Wildlife Toxicity Assessments for Chemicals of Military Concern*, pp. 291–301, 2015. https://doi.org/10.1016/B978-0-12-800020-5.00017-X

[38] H. Nosal, K. Moser, M. Warzała, A. Holzer, D. Stańczyk, and E. Sabura, "Selected Fatty Acids Esters as Potential PHB-V Bioplasticizers: Effect on Mechanical Properties of the Polymer," *Journal of Polymers and the Environment*, vol. 29, no. 1, pp. 38–53, 2020. https://doi.org/10.1007/S10924-020-01841-5

[39] M. Johar, K. Z. Zarkasi, N. A. M. Zaini, and A. Rusli, "Enhancement of mechanical, rheological and antifungal properties of polylactic acid/ethylene–vinyl-acetate blend by triacetin plasticizer," *Journal of Polymer Research*, vol. 30, no. 7, pp. 1–19, 2023. https://doi.org/10.1007/S10965-023-03630-9

[40] P. Khatri, D. Desai, N. Shelke, and T. Minko, "Role of plasticizer in membrane coated extended release oral drug delivery system," *Journal of Drug Delivery Science and Technology*, vol. 44, pp. 231–243, 2018. https://doi.org/10.1016/J.JDDST.2017.12.020

[41] P. Mukhopadhyay, R. Chakraborty, and S. Singh, "Triacetin additive in biodiesel to reduce air pollution: a review," *Environmental Chemistry Letters*, vol. 20, no. 2, pp. 1193–1224, 2022. https://doi.org/10.1007/s10311-021-01362-0

[42] D. Koedthip, E. Kalkornsurapranee, K. Sengloyluan, P. Songtipya, and L. Songtipya, "Enhancing the Ductility and Properties of Non-Vulcanized Polylactic Acid-Based Thermoplastic Natural Rubber Using Acetyl Tributyl Citrate," *Polymers*, vol. 17, no. 5, 2025. https://doi.org/10.3390/polym17050601

[43] X. Lin *et al.*, "Effect of Acetyl tributyl citrate on bone metabolism based on network toxicology and molecular docking technology," *Ecotoxicology and Environmental Safety*, vol. 289, p. 117434, 2025. https://doi.org/10.1016/J.ECOENV.2024.117434

[44] O. Adiyanto, E. Mohamad, Irianto, R. Jaafar, M. Faishal, and M. I. Rasyid, "Optimization of PET Particle-Reinforced Epoxy Resin Composite for Eco-Brick Application Using the Response Surface Methodology," *Sustainability*, vol. 15, no. 5, 2023. https://doi.org/10.3390/su15054271

[45] J. C. Wu, J. Y. Chang, X. Yuan, E. Khan, Y. S. Ok, and C. H. Hou, "Upcycling waste polyethylene terephthalate (PET) bottles into high-performance activated carbon for electrochemical desalination," *Chemosphere*, vol. 364, 2024. https://doi.org/10.1016/j.chemosphere.2024.143029

[46] A. B. S, V. R. Modi, and H. J. Patel, "Study on Melted Waste Plastic Bottles as Binder in Plastic Mortar," pp. 1–4, 2020. https://doi.org/10.2139/ssrn.3696554

[47] D. Mentes *et al.*, "Combustion behaviour of plastic waste – A case study of PP, HDPE, PET, and mixed PES-EL," *Journal of Cleaner Production*, vol. 402, p. 136850, 2023. https://doi.org/10.1016/J.JCLEPRO.2023.136850

[48] M. Râpă *et al.*, "Effect of plasticizers on melt processability and properties of PHB," *Journal of Optoelectronics and Advanced Materials*, vol. 17, no. 11–12, pp. 1778–1784, 2015.

[49] M. Raheel Bawani, A. I. Arol, G. Tozsin, A. Torun, M. R. Bawani, and T. Oltu-Stone, "Petrographical and chemical characteristics of cleaned oltu-stone waste for their potential use (as a semi-precious stone)," *Mehran University Research Journal of Engineering and Technology*, vol. 44, no. 3, pp. 94–105, 2025. https://doi.org/10.22581/muet1982.0272

[50] J. A. D'Angelo, E. L. Zodrow, and J. Pšenička, "3D Chemometric Model Simulating the Acitheca Polymorpha Frond: Implications for Reconstructing Carboniferous Ferns (Marattiales, Canada)," *Folia Musei rerum naturalium Bohemiae occidentalis. Geologica et Paleobiologica*, vol. 55, no. 1–2, pp. 1–21, 2021. https://doi.org/10.2478/fbgp-2021-0001

UMP Press