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Synergistic Enhancement of Mechanical and Thermal Properties of Hybrid Polyvinyl Chloride Composites Modified with Polyvinyl Acetate, Epoxidized Soybean Oil and Graphene Oxide

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Abstract

Polyvinyl chloride (PVC) composites modified with polyvinyl acetate (PVAc), epoxidized soybean oil (ESO), and graphene oxide (GO) were developed to investigate the synergistic effects of hybrid modification on mechanical and thermal properties. The composites were prepared using melt mixing followed by compression moulding. Tensile properties were evaluated in accordance with ASTM D638 standards, while thermal stability was assessed using thermogravimetric analysis (TGA). Statistical analysis was performed using mean ± standard deviation (SD), 95% confidence intervals (CI), and one-way ANOVA analysis showed statistically significant differences among tensile strength values of the modified composites ($F = 16.97$, $p < 0.05$). Neat PVC exhibited a tensile strength of 44.29 ± 0.52 MPa, while PVC/ESO_2 recorded the highest tensile strength of 89.23 ± 4.33 MPa. Hybrid formulations demonstrated improved mechanical performance, with PVC/H1 exhibiting balanced tensile strength (76.09 ± 4.90 MPa) and elongation (12.45 ± 1.16%). Thermal analysis confirmed enhanced stability in modified systems compared to neat PVC. The results demonstrate that hybrid modification significantly improves mechanical and thermal performance of PVC composites, indicating their suitability for advanced engineering applications.

Keywords: Polyvinyl chloride, Hybrid composites, Epoxidized soybean oil, Polyvinyl acetate, Graphene oxide, Mechanical properties, Hybrid modification

1. INTRODUCTION

Polyvinyl Chloride (PVC) remains one of the most widely utilized thermoplastic polymers due to its versatility, durability, chemical resistance, and relatively low production cost (Akhina *et al*., 2024).. The material has found extensive applications in construction materials, pipes, cable insulation, packaging films, flooring materials, and protective coverings due to its favourable mechanical and chemical properties (Deshmukh and Joshi, 2014; Rahmah *et al*., 2017).

Despite these advantages, unmodified PVC exhibits inherent limitations such as brittleness, limited flexibility, and susceptibility to thermal degradation during processing and service conditions. These limitations restrict its application in environments requiring improved toughness, flexibility, and thermal resistance (Kuilla *et al*., 2010; Wang *et al*., 2024).

To overcome these limitations, several modification strategies have been developed, including plasticization, polymer blending, and reinforcement using nanoscale fillers. Among these strategies, the use of environmentally friendly plasticizers has gained significant attention due to increasing concerns over the toxicity of conventional phthalate plasticizers. Epoxidized Soybean Oil (ESO) has emerged as an effective bio-based plasticizer due to the presence of reactive epoxide functional groups capable of improving flexibility and enhancing thermal stabilization of PVC systems (Rahmah *et al*., 2017; Boraei *et al*., 2024).

ESO contributes to increased chain mobility within the polymer matrix, thereby improving ductility and reducing brittleness. Additionally, the epoxy groups present in ESO have been reported to interact with hydrogen chloride released during thermal degradation of PVC, thereby delaying degradation reactions and improving thermal stability (Deshmukh and Joshi, 2014; Boraei *et al*., 2024).

Another effective strategy for improving the mechanical performance of PVC involves polymer blending. Polyvinyl Acetate (PVAc) has been widely used as a compatible polymer for PVC due to the presence of polar ester functional groups, which promote intermolecular interactions between polymer chains. The incorporation of PVAc into PVC matrices has been associated with improved flexibility, enhanced toughness, and improved compatibility within polymer blends (Lekshmi *et al*., 2024).

In recent years, the development of polymer nanocomposites has introduced new possibilities for improving mechanical strength and thermal resistance of polymer systems. Among the available nanomaterials, Graphene Oxide (GO) has attracted considerable research attention due to its high surface area, layered structure, and abundance of oxygen-containing functional groups. These structural features enable strong interfacial bonding between GO sheets and polymer matrices, thereby improving mechanical reinforcement and thermal resistance (Kuilla *et al.,* 2010; Huang *et al.*, 2024).

The incorporation of GO into polymer systems has been reported to improve tensile strength, modulus, and thermal stability through improved stress transfer and restricted polymer chain mobility. However, uniform dispersion of GO within polymer matrices remains a critical factor influencing overall composite performance (Kuilla *et al*., 2010; Wang *et al*., 2024).

While several studies have investigated the individual effects of plasticizers, polymer modifiers, and nanofillers on PVC properties, many of these investigations have focused on single-modifier systems. Although such approaches improve selected properties, they often fail to provide balanced performance across mechanical and thermal parameters required for advanced engineering applications (Rahmah *et al*., 2017; Lekshmi *et al*., 2024).

Hybrid modification strategies involving simultaneous incorporation of multiple modifiers have recently gained attention due to their potential to produce synergistic property enhancement. In hybrid systems, each component performs a complementary function. For example, ESO improves flexibility and thermal stabilization, PVAc enhances compatibility and interfacial adhesion, while GO contributes mechanical reinforcement and thermal resistance (Huang *et al*., 2024; Wang *et al*., 2024).

Despite growing interest in hybrid polymer systems, limited studies have systematically evaluated the combined influence of ESO, PVAc, and GO within a single PVC matrix while establishing clear structure–property relationships supported by mechanical, thermal, and morphological characterization.

Therefore, this study investigates the hybrid modification of PVC using PVAc, ESO, and GO through controlled formulation techniques. The prepared composite systems were evaluated using mechanical testing, and Thermogravimetric Analysis (TGA) to establish relationships between composition, and performance.

The findings from this study are expected to provide valuable insight into the development of high-performance PVC-based hybrid composites suitable for advanced engineering and protective material applications.

2. MATERIALS AND METHODS

2.1 Materials

The base polymer used in this study was Polyvinyl Chloride (PVC) resin of commercial grade. The modifying agents incorporated into the PVC matrix included Polyvinyl Acetate, Epoxidized Soybean Oil, and Graphene Oxide.

Calcium–zinc stabilizer (1.5 g) and stearic acid (1 g) were used as stabilizing and lubricating agents, respectively, during the formulation process to enhance thermal stability and improve processability of the polymer blends.

2.2 Methods

All materials were used as received without further purification. The compositions of the formulated composites were prepared using phr (parts per hundred resin) based on the weight of PVC resin. The formulation ratios for the prepared composites are presented in Table 1 – 4.

Table 1: Formulation of ESO-Modified PVC Composites (PVC Basis = 100 g)

Sample ID	PVC (g)	ESO (phr)	ESO (g)	Ca/Zn (g)	Stearic acid (g)
ESO$_0$	100	0	0.0	1.5	1.0
ESO$_5$	100	5	5.0	1.5	1.0
ESO$_{10}$	100	10	10.0	1.5	1.0
ESO$_{15}$	100	15	15.0	1.5	1.0
ESO$_{20}$	100	20	20.0	1.5	1.0

Table 2: Formulation of PVAc-Modified PVC Composites (Polymer Basis = 100 g)

Sample ID	PVC (g)	PVAc (wt%)	PVAc (g)	Ca/Zn (g)	Stearic acid g)
PVAc$_0$	100	0	0.0	1.5	1.0
PVAc$_5$	95	5	5.0	1.5	1.0
PVAc$_{10}$	90	10	10.0	1.5	1.0
PVAc$_{15}$	85	15	15.0	1.5	1.0
PVAc$_{20}$	80	20	20.0	1.5	1.0

Table 3: Formulation of GO-Filled PVC Composites (PVC Basis = 100 g)

Sample ID	PVC (g)	GO (wt%)	GO (g)	Ca/Zn (g)	Stearic acid (g)
GO$_0$	100	0	0.0	1.5	1.0
GO$_{0.5}$	100	0.5	0.5	1.5	1.0
GO$_{1.0}$	100	1.0	1.0	1.5	1.0
GO$_{1.5}$	100	1.5	1.5	1.5	1.0
GO$_{2.0}$	100	2.0	2.0	1.5	1.0

Table 4: Formulation of Hybrid Modified PVC Composites (Polymer Basis = 100 g)

Sample ID	PVC (g)	PVAc (g)	ESO (g)	GO (g)	Ca/Zn (g)	Stearic acid (g)
H1	100.0	0.0	10.0	1.0	1.5	1.0
H2	95.0	5.0	10.0	1.0	1.5	1.0
H3	90.0	10.0	10.0	1.0	1.5	1.0
H4	85.0	15.0	10.0	1.0	1.5	1.0
H5	80.0	20.0	10.0	1.0	1.5	1.0

2.3 Preparation of Composite Formulations

Composite formulations were prepared using a multi-stage processing technique involving dry blending, melt mixing using a two-roll mill, and compression moulding.

2.4 Dry Blending Process

The measured quantity of PVC resin was initially dry-blended with 1.5 g calcium–zinc stabilizer and 1 g stearic acid lubricant to ensure preliminary homogenization of the base polymer system. The blending was carried out using a laboratory blender to achieve uniform dispersion of additives within the PVC matrix.

For formulations containing graphene oxide (GO), the GO particles were pre-dispersed in a small portion of epoxidized soybean oil (ESO) using a magnetic stirrer for 15–20 minutes. This pre-dispersion step was introduced to minimize agglomeration of GO particles and to improve interfacial interaction between GO and the polymer matrix. The dry-blended materials were subsequently transferred to the melt-processing stage.

2.5 Melt Mixing Using Two-Roll Mill

Thermal blending of the prepared mixtures was carried out using a two-roll mill operating at a temperature of 180 °C. The materials were processed under continuous mixing until homogeneous polymer sheets were formed. The elevated processing temperature ensured sufficient softening of PVC and promoted uniform dispersion of PVAc, ESO, and GO throughout the polymer matrix. The molten sheets obtained from the two-roll mill were collected and prepared for moulding operations.

2.6 Compression Moulding Process

Compression moulding of the compounded materials was carried out using a compression moulding machine under controlled processing conditions. The moulding parameters used were:

Moulding temperature: 170 °C
Applied pressure: 10 MPa
Holding time: 5 minutes

After moulding, the samples were cooled under sustained pressure of 10 MPa until room temperature was reached. Cooling under pressure was necessary to prevent deformation, shrinkage, and warping of the moulded sheets.

The moulded samples were subsequently conditioned at ambient laboratory conditions for 48 hours prior to mechanical and thermal testing to ensure dimensional stability and reproducibility of results. Standardized test specimens were prepared from the moulded sheets according to specified testing requirements.

2.7 Mechanical Property Testing

Mechanical properties of the prepared composite samples were evaluated using standard testing procedures in accordance with established ASTM methods.

2.7.1 Tensile Testing

Tensile properties including tensile strength, modulus of elasticity, and elongation at break were determined using ASTM D638 standard procedures. Standard dumbbell-shaped specimens were prepared from compression-moulded sheets, and testing was carried out using a universal testing machine under controlled laboratory conditions. The average values obtained from multiple specimens were recorded to ensure accuracy and reproducibility.

2.8 Thermogravimetric Analysis (TGA)

Thermal stability of the composite materials was evaluated using thermogravimetric analysis (TGA). The TGA analysis was conducted under the following operating conditions:

Temperature range: 30–900 °C
Heating rate: 10 °C/min
Atmosphere: Nitrogen
Nitrogen flow rate: 60 mL/min
Sample mass: 5–19 mg

Calibration of the thermogravimetric instrument was carried out in accordance with ASTM E1582-17 to ensure accuracy of temperature and weight measurements. The obtained thermograms were used to determine thermal degradation behaviour, weight loss characteristics, and residual char yield of the prepared composites.

2.9 Statistical Analysis

Statistical analysis of mechanical properties was performed using three replicate measurements ($n = 3$) for each sample. Results are presented as mean ± standard deviation (SD). The 95% confidence intervals (CI) were calculated using Student's t-distribution at a 95% confidence level. One-way analysis of variance (ANOVA) was conducted to evaluate statistical differences among composite formulations at a significance level of $p < 0.05$.

3.0 RESULTS AND DISCUSSION

3.1 Mechanical Properties of Modified PVC Composites

The mechanical properties of polymer composites provide valuable insight into the structural integrity and performance capability of the material under applied stress. In this study, the mechanical behaviour of modified Polyvinyl Chloride systems containing Polyvinyl Acetate, Epoxidized Soybean Oil, and Graphene Oxide was evaluated through tensile strength, modulus of elasticity, and elongation at break. The observed trends provide evidence of synergistic interactions among the modifying components.

3.2 Tensile Strength Behaviour

Tensile strength is a critical parameter that reflects the ability of a material to withstand applied stress without failure. The tensile strength values obtained for the modified PVC systems showed significant variation depending on the type and combination of modifiers incorporated into the polymer matrix (Mamza, *et al*).

3.3 Statistical Analysis

Standard Deviation (SD)

$$SD = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$$

Confidence Interval (95%)

$$CI = \bar{x} \pm t\left(\frac{SD}{\sqrt{n}}\right)$$

where:

$\bar{x}$ = Mean
t = t-value
SD = Standard deviation
n = Number of trials

Tensile strength results were obtained from three replicate measurements ($n = 3$) and expressed as mean ± standard deviation to demonstrate reproducibility and statistical reliability of the mechanical performance of the prepared composites.

Table 5: Tensile Strength Replicates of PVC-Based Composites with Statistical Analysis

S/N	Sample	Rep 1	Rep 2	Rep 3	Mean (MPa) ± SD (MPa)
1	PVC	44.13	43.87	44.87	44.29 ± 0.52
2	PVC/ESO1	75.60	78.67	62.40	72.22 ± 8.70
3	PVC/ESO2	84.23	91.73	91.73	89.23 ± 4.33
4	PVC/ESO3	84.80	90.00	82.00	85.60 ± 4.10
5	PVC/ESO4	36.93	49.47	41.33	42.58 ± 6.31
6	PVC/PVAc1	54.80	57.07	51.33	54.40 ± 2.89
7	PVC/PVAc2	51.07	53.73	41.87	48.89 ± 6.34
8	PVC/PVAc3	51.47	43.60	53.60	49.56 ±5.36
9	PVC/PVAc4	46.67	45.07	46.13	45.96 ± 0.81
10	PVC/GO1	30.83	34.40	30.08	31.77± 2.33
11	PVC/GO2	60.00	52.13	49.60	53.91 ± 5.42
12	PVC/GO3	46.40	63.47	62.00	57.29 ± 9.41
13	PVC/GO4	58.53	61.33	65.33	61.73 ± 3.40
14	PVC/H1	70.53	79.73	78.00	76.09 ± 4.90
15	PVC/H2	68.93	71.07	64.93	68.31 ± 3.16
16	PVC/H3	62.93	60.80	54.40	59.38 ± 4.46
17	PVC/H4	51.07	64.93	36.00	50.67± 14.46
18	PVC/H5	30.53	42.67	54.67	42.62± 12.08

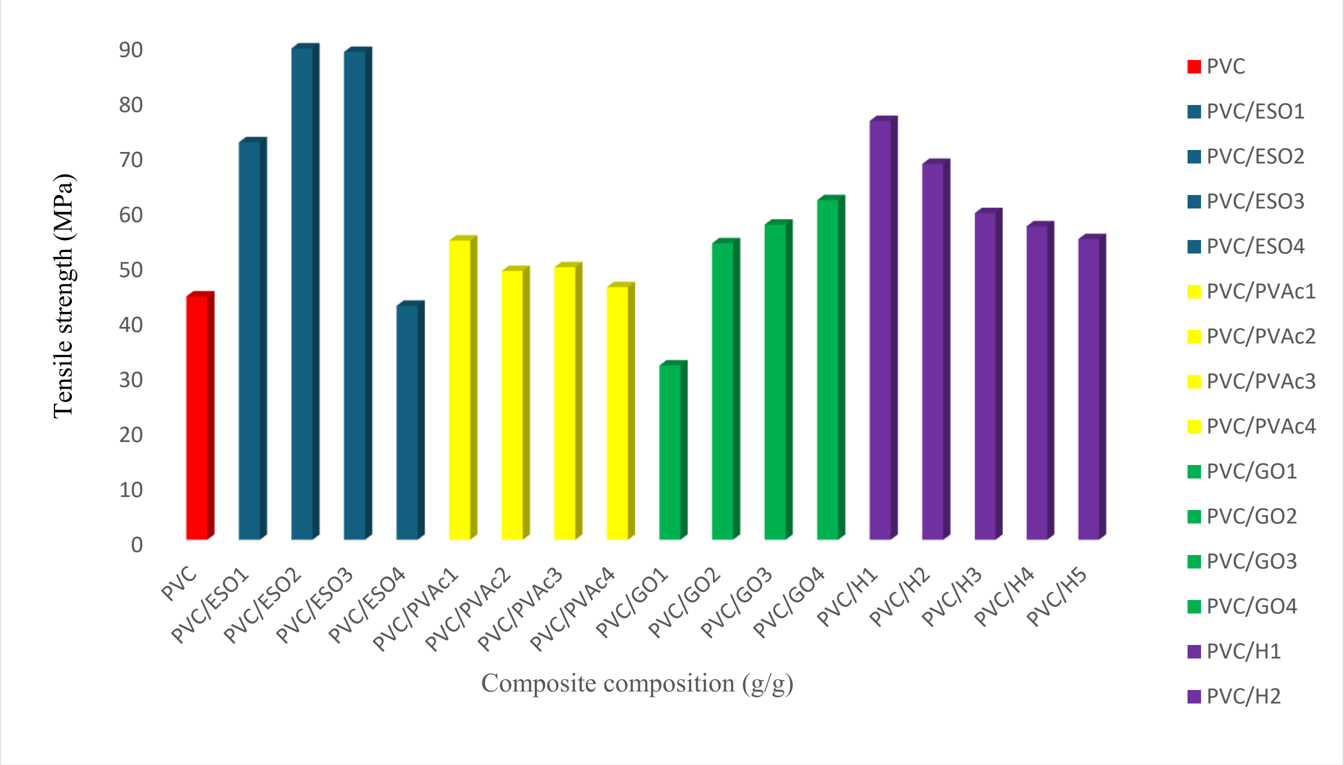

Fig. 1: Tensile Strength of PVC and modified composites showing the effect of ESO, PVAc, GO, and hybrid modification

Table 6: Elongation at Break (%) of PVC-Based Composites (Mean ± SD, n = 3)

S/N	Sample	Rep 1	Rep 2	Rep 3	Mean (%)	SD (%)
1	PVC	12.48	7.34	9.32	9.71	2.58
2	PVC/ESO1	12.02	11.79	9.91	11.24	1.16
3	PVC/ESO2	13.71	10.01	10.01	11.24	2.14
4	PVC/ESO3	12.89	6.70	9.73	9.77	3.10
5	PVC/ESO4	7.80	8.67	7.16	7.88	0.76
6	PVC/PVAc1	11.70	11.88	9.77	11.12	1.16
7	PVC/PVAc2	11.15	11.42	10.32	10.96	0.57
8	PVC/PVAc3	10.00	7.85	10.65	9.50	1.50
9	PVC/PVAc4	12.06	8.21	10.09	10.12	1.93
10	PVC/GO1	8.35	6.98	4.36	6.56	2.02
11	PVC/GO2	23.21	10.41	10.51	14.71	7.37
12	PVC/GO3	8.31	13.17	10.78	10.75	2.43
13	PVC/GO4	11.88	11.10	11.97	11.65	0.48
14	PVC/H1	11.15	12.89	13.31	12.45	1.16
15	PVC/H2	10.05	10.14	9.96	10.05	0.09
16	PVC/H3	10.73	9.45	10.65	10.28	0.71
17	PVC/H4	6.56	8.35	6.66	7.19	1.00
18	PVC/H5	4.87	7.80	9.63	7.43	2.39

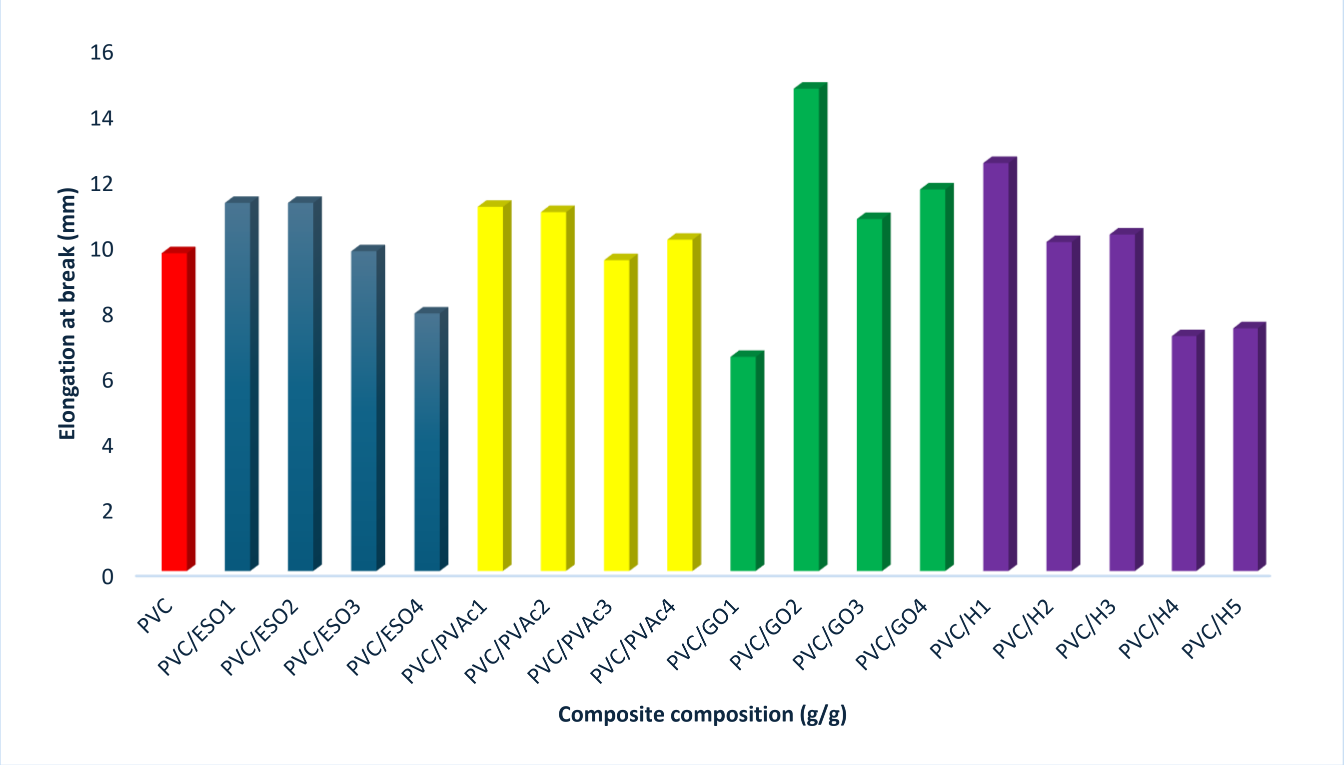

Fig. 2: Elongation at Break of PVC and modified composites showing the effect of ESO, PVAc, GO, and hybrid modification

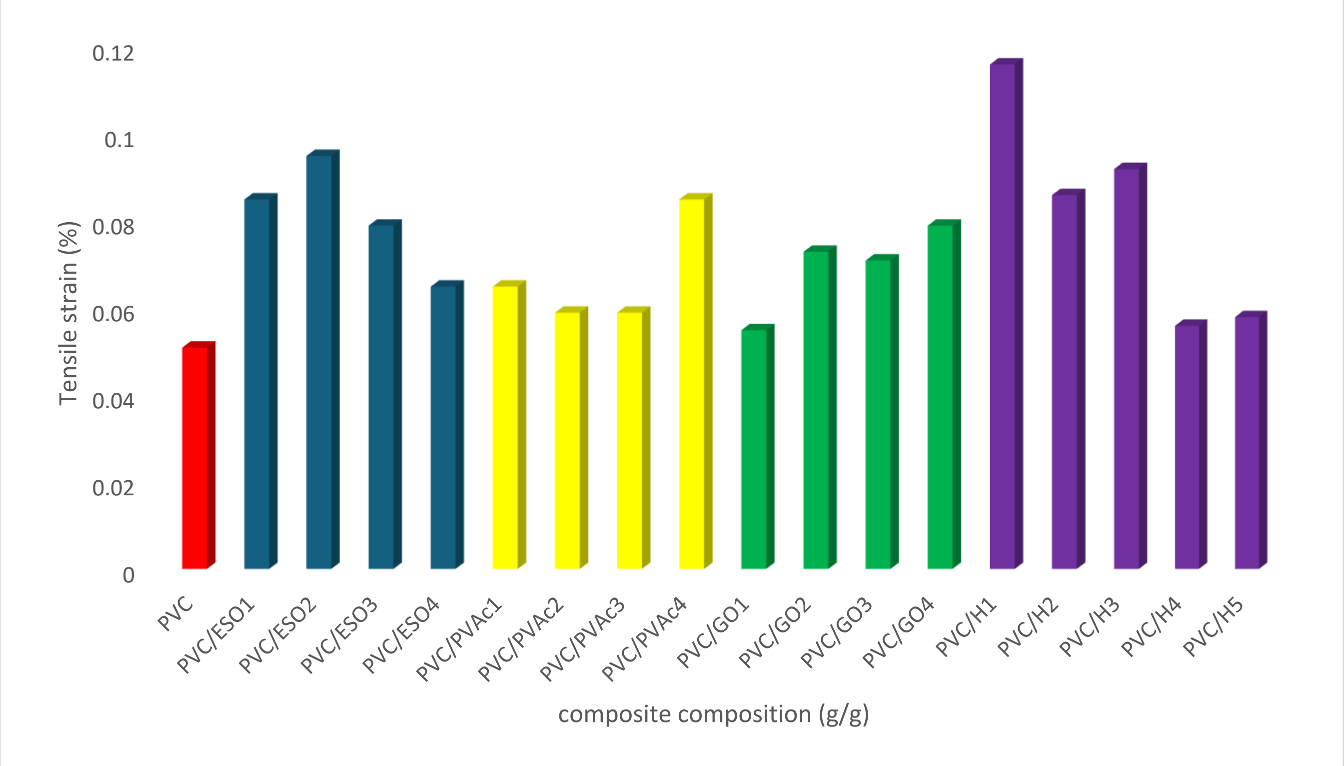

Fig. 3: Tensile Strain of PVC and modified composites showing the effect of ESO, PVAc, GO, and hybrid modification

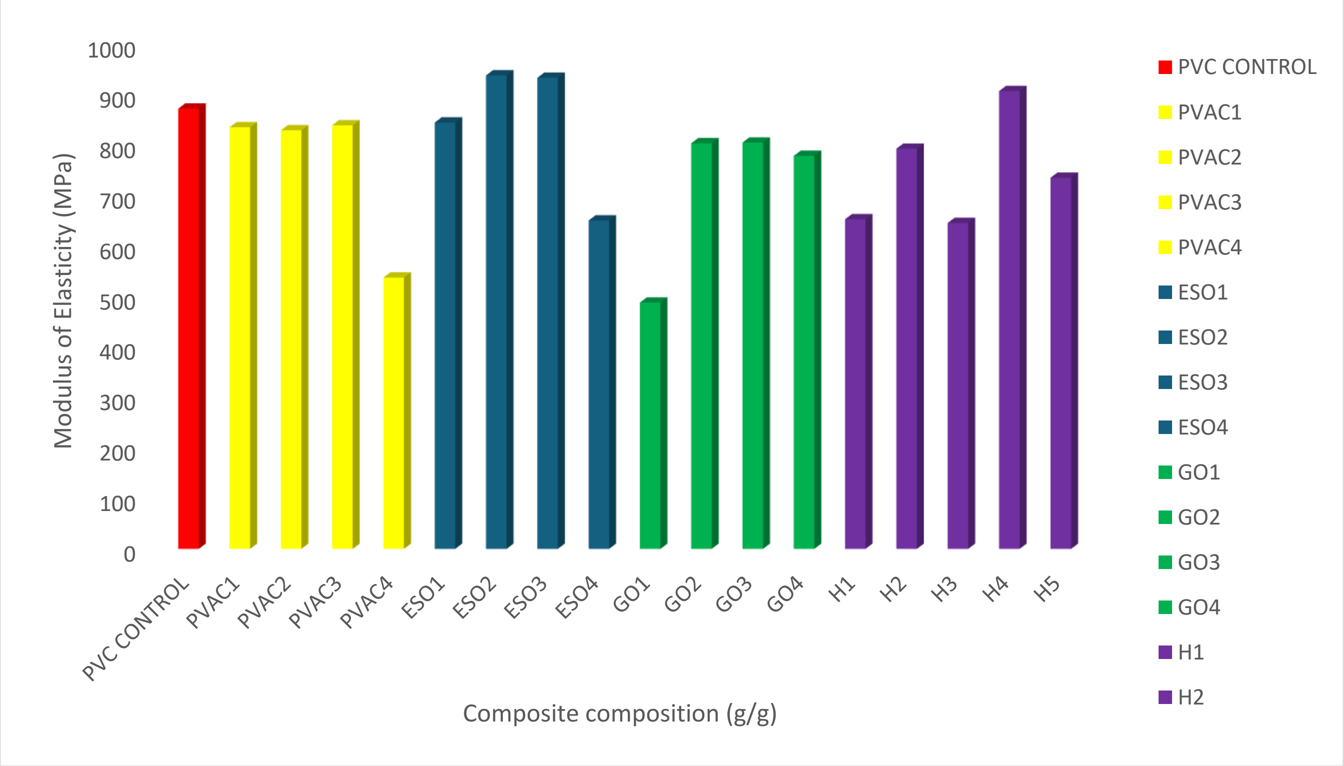

Fig. 4: Elastic Modulus of PVC and modified composites showing the effect of ESO, PVAc, GO, and hybrid modification

Table 7: Elastic Modulus of PVC-Based Composites (MPa) (Mean ± SD, n = 3)

S/N	Sample	Mean (MPa)	SD (MPa)
1	PVC	874.20	130.80
2	PVC/ESO1	846.64	83.24
3	PVC/ESO2	939.84	261.35
4	PVC/ESO3	935.18	238.52
5	PVC/ESO4	652.80	118.53
6	PVC/PVAc1	837.19	112.56
7	PVC/PVAc2	831.27	135.18
8	PVC/PVAc3	841.06	188.58
9	PVC/PVAc4	539.81	58.59
10	PVC/GO1	490.34	123.42
11	PVC/GO2	805.58	133.60
12	PVC/GO3	806.90	6.89
13	PVC/GO4	780.78	83.49
14	PVC/H1	655.30	22.87
15	PVC/H2	794.75	104.30
16	PVC/H3	647.88	84.09
17	PVC/H4	908.93	327.79
18	PVC/H5	737.36	200.14

Table 8: Tensile Strength with 95% Confidence Interval (Mean ± SD, 95% CI, n = 3, t = 4.303)

Sample	Mean (MPa)	SD (MPa)	95% CI (MPa)
PVC	44.29	0.52	44.29 ± 1.29
PVC/ESO1	72.22	8.70	72.22 ± 21.62
PVC/ESO2	89.23	4.33	89.23 ± 10.76
PVC/ESO3	85.60	4.10	85.60 ± 10.18
PVC/ESO4	42.58	6.31	42.58 ± 15.67
PVC/PVAc1	54.40	2.89	54.40 ± 7.18
PVC/PVAc2	48.89	6.34	48.89 ± 15.76
PVC/PVAc3	49.56	5.36	49.56 ± 13.32
PVC/PVAc4	45.96	0.81	45.96 ± 2.01
PVC/GO1	31.77	2.33	31.77 ± 5.79
PVC/GO2	53.91	5.42	53.91 ± 13.48
PVC/GO3	57.29	9.41	57.29 ± 23.39
PVC/GO4	61.73	3.40	61.73 ± 8.45
PVC/H1	76.09	4.90	76.09 ± 12.17
PVC/H2	68.31	3.16	68.31 ± 7.86
PVC/H3	59.38	4.46	59.38 ± 11.08
PVC/H4	50.67	14.46	50.67 ± 35.93
PVC/H5	42.62	12.08	42.62 ± 30.04

3.4 Mechanical Properties of PVC-Based Composites

3.4.1 Tensile Strength

The tensile strength of the prepared PVC-based composites showed significant variation depending on the type and concentration of modifiers incorporated into the polymer matrix. The neat polyvinyl chloride (PVC) exhibited a tensile strength of 44.29 ± 0.52 MPa, which served as the baseline for evaluating the performance of the modified systems. The incorporation of epoxidized soybean oil (ESO) significantly improved the tensile strength of the composites, with the PVC/ESO2 formulation exhibiting the highest tensile strength of 89.23 ± 4.33 MPa, representing a substantial enhancement compared to the unmodified PVC.

The improvement in tensile strength observed in the ESO-modified systems can be attributed to the plasticizing and stabilizing effects of epoxidized oils, which enhance polymer chain mobility while maintaining intermolecular cohesion. Epoxidized vegetable oils have been reported to improve compatibility and stress transfer efficiency within PVC matrices due to the presence of reactive epoxy groups that interact with the polymer backbone (Bueno-Ferrer *et al*., 2010; Rahmah *et al*., 2017). Similarly, Bouchareb and Benaniba (2008) reported that epoxidized oils act as effective plasticizers capable of enhancing tensile performance while reducing brittleness in PVC systems.

In contrast, excessive plasticizer loading, as observed in the PVC/ESO4 formulation (42.58 ± 6.31 MPa), resulted in a reduction in tensile strength relative to ESO2 and ESO3. This decrease can be attributed to over-plasticization, which reduces intermolecular interactions and weakens the polymer network structure. Such reductions at higher plasticizer content have been widely reported in PVC-based systems where excessive plasticizer disrupts polymer chain cohesion (Satapathy and Palanisamy, 2021).

The incorporation of polyvinyl acetate (PVAc) also influenced tensile strength behaviour. The PVC/PVAc1 sample exhibited a tensile strength of 54.40 ± 2.89 MPa, indicating moderate improvement compared to neat PVC. This enhancement may be attributed to the compatibility between PVC and PVAc phases, leading to improved stress distribution within the polymer matrix. Previous studies have reported that PVAc-containing blends exhibit improved mechanical integrity due to partial miscibility and improved interfacial adhesion between polymer phases (Jaffe *et al.,* 2020; Flores-Guía *et al.,* 2024).

Graphene oxide (GO) incorporation produced varied results depending on loading concentration. The PVC/GO4 composite recorded a tensile strength of 61.73 ± 3.40 MPa, demonstrating improved mechanical strength relative to neat PVC. This improvement can be attributed to the reinforcing capability of graphene oxide, which enhances load transfer efficiency when adequately dispersed within the polymer matrix. Similar enhancements have been reported in graphene oxide-reinforced PVC composites, where improved mechanical properties were associated with strong filler–matrix interaction and improved stress transfer mechanisms (Deshmukh and Joshi, 2014; Mindivan, 2019).

Hybrid formulations demonstrated synergistic performance characteristics, particularly the PVC/H1 composite, which exhibited a tensile strength of 76.09 ± 4.90 MPa. The improved performance observed in hybrid systems suggests cooperative interaction between multiple modifiers, leading to enhanced mechanical stability and stress distribution. Hybrid reinforcement strategies have been reported to improve the mechanical performance of polymer composites by combining the plasticizing and reinforcing effects of different modifiers (Sharma *et al.,* 2026).

3.4.2 Elongation at Break

Elongation at break is an important parameter that reflects the ductility and flexibility of polymeric materials. The neat PVC sample exhibited an elongation at break of 9.71 ± 2.58 %, indicating relatively limited flexibility typical of unplasticized PVC materials.

The addition of ESO significantly enhanced elongation properties, particularly in the PVC/ESO1 and PVC/ESO2 samples, both exhibiting elongation values of 11.24 %, indicating improved ductility. The increase in elongation observed in ESO-modified systems is attributed to the plasticizing effect of epoxidized oils, which increases free volume and reduces intermolecular friction, allowing polymer chains to move more freely under tensile stress. Similar increases in elongation have been reported in PVC systems plasticized with epoxidized soybean oil and other bio-based plasticizers (Rahmah *et al*., 2017; Zhang *et al.,* 2021).

PVAc-modified samples also exhibited enhanced elongation characteristics, with PVC/PVAc1 recording 11.12 ± 1.16 %, indicating improved flexibility relative to neat PVC. The presence of PVAc contributes to increased flexibility due to its relatively soft and ductile nature, which enhances the ability of the polymer matrix to deform before fracture (Flores-Guía *et al*., 2024).

Graphene oxide-modified samples displayed variable elongation values. The PVC/GO2 composite exhibited the highest elongation among GO-modified samples (14.71 ± 7.37 %), suggesting improved flexibility under optimal loading conditions. However, variability observed in GO-modified samples may be associated with differences in filler dispersion and distribution within the matrix, which significantly influence mechanical response (Guo and Cai, 2022).

Hybrid composites demonstrated notable improvements in elongation behaviour, particularly PVC/H1 (12.45 ± 1.16 %), indicating enhanced flexibility resulting from synergistic interactions among the incorporated modifiers. Hybrid modification strategies have been reported to improve ductility and toughness by combining multiple mechanisms of stress absorption and energy dissipation (Sharma *et al.,* 2026).

3.4.3 Modulus of Elasticity

The modulus of elasticity reflects the stiffness of polymer composites and their resistance to elastic deformation under applied stress. The neat PVC exhibited a modulus of 874.20 ± 130.80 MPa, indicating moderate stiffness characteristic of unmodified PVC materials.

ESO-modified composites displayed varied modulus values depending on loading concentration. The PVC/ESO2 sample exhibited the highest modulus among ESO formulations (939.84 ± 261.35 MPa), suggesting improved stiffness and structural integrity at optimal plasticizer concentration. Moderate increases in modulus in plasticized PVC systems have been reported when plasticizer content is carefully controlled to maintain structural stability while enhancing flexibility (Rahmah *et al.,* 2017).

PVAc incorporation resulted in moderate modulus values, with PVC/PVAc1 recording 837.19 ± 112.56 MPa, indicating slightly reduced stiffness compared to neat PVC. This behaviour is consistent with the plasticizing nature of PVAc, which increases polymer flexibility while reducing rigidity (Jaffe *et al.,* 2020).

Graphene oxide-modified composites showed stiffness enhancement at appropriate loading levels. The PVC/GO3 composite exhibited a modulus of 806.90 ± 6.89 MPa, indicating consistent stiffness performance with minimal variability. Reinforcement with graphene-based fillers has been widely reported to improve stiffness due to their high aspect ratio and mechanical strength (Deshmukh and Joshi, 2014; Xiao *et al.,* 2018).

Hybrid composites demonstrated balanced mechanical performance, with PVC/H4 exhibiting a relatively high modulus (908.93 ± 327.79 MPa), indicating increased resistance to deformation under applied stress. The improved stiffness observed in hybrid systems may be attributed to combine reinforcing and stabilizing effects of multiple modifiers (Sharma *et al.,* 2026).

Summarily, the mechanical results demonstrate that modifier type and concentration significantly influenced the tensile behaviour of PVC-based composites. The incorporation of epoxidized soybean oil resulted in substantial improvements in tensile strength and elongation at optimal loading levels, while excessive plasticizer addition reduced mechanical stability. PVAc modification improved ductility and moderate strength, whereas graphene oxide provided reinforcement effects that enhanced stiffness and mechanical stability.

Hybrid formulations exhibited synergistic performance, producing balanced mechanical properties suitable for structural and flexible PVC-based applications.

3.5 ANOVA Results for Tensile Strength of PVC Composites

One-way analysis of variance (ANOVA) was performed to determine the statistical significance of differences among the tensile strength values of the modified PVC composites. Statistical significance was evaluated at a confidence level of 95% ($p < 0.05$).

One-way analysis of variance (ANOVA) revealed statistically significant differences among the tensile strength values of the modified PVC composites ($F = 16.97$, $p < 0.05$), indicating that modifier composition significantly influenced the mechanical performance of the prepared materials.

Table 9: One-Way ANOVA Results for Tensile Strength of PVC Composites

Source of Variation	Sum of Squares (SS)	Df	Mean Square (MS)	F-value	p-value
Between Groups	10445.68	17	614.45	16.97	2.46×10^{-12}
Within Groups	1303.34	36	36.20	—	—
Total	11749.02	53	—	—	—

3.6 Thermogravimetric Analysis (TGA) — Thermal Behaviour

Thermal stability of the prepared composite systems based on Polyvinyl Chloride was evaluated using thermogravimetric analysis (TGA) under a nitrogen atmosphere over a temperature range of 30–900 °C at a heating rate of 10 °C min^{-1}. The obtained thermograms provided valuable insight into the degradation behaviour and thermal resistance of the modified PVC systems.

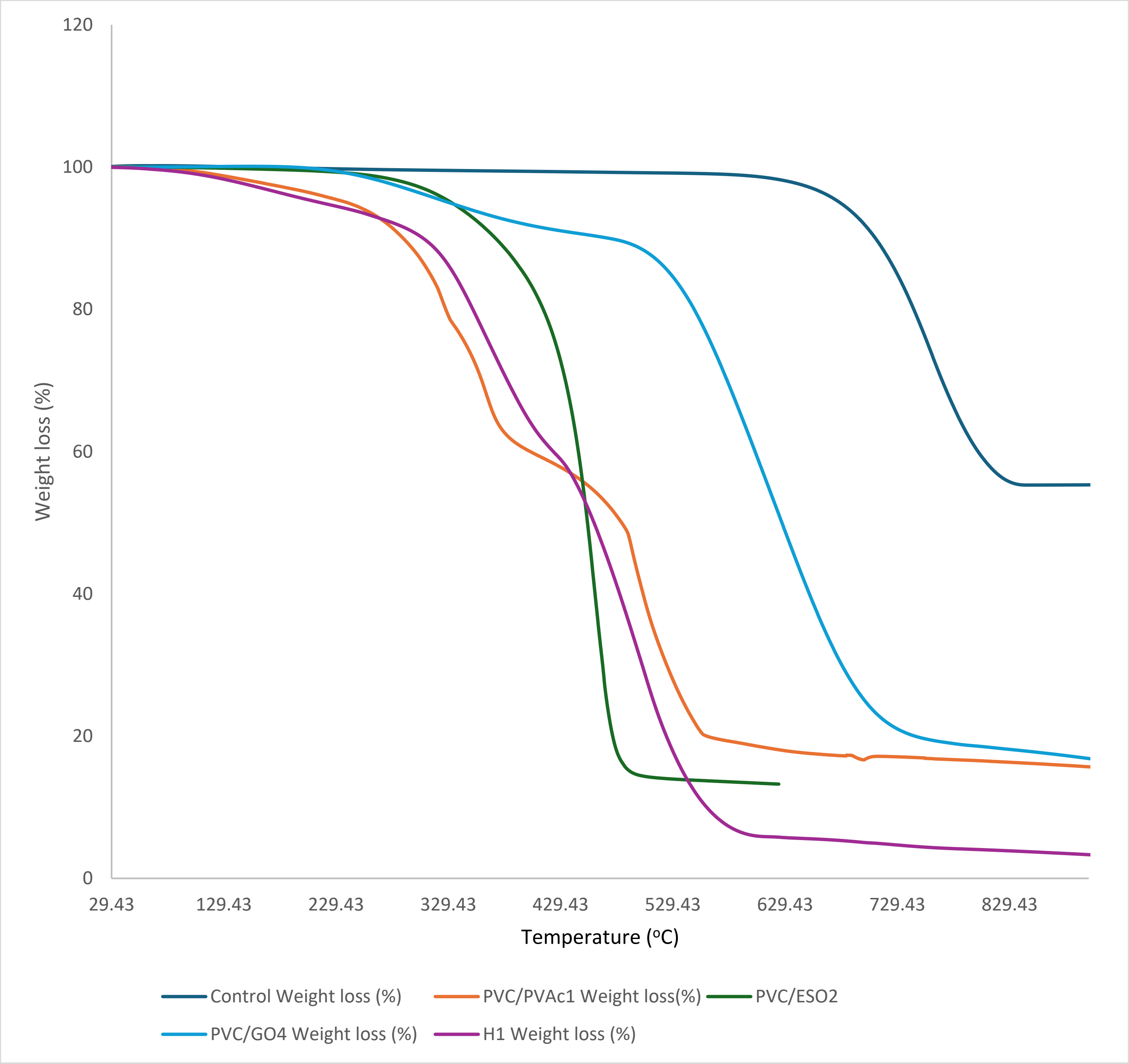

Fig. 5: TGA Thermogram of Virgin PVC, Single Modifiers and / Hybrid (H1) Composite

Virgin PVC exhibited a typical two-stage degradation profile characteristic of chlorinated polymers. The initial stage of thermal degradation occurred between approximately 250 °C and 350 °C, corresponding to dehydrochlorination, during which hydrogen chloride (HCl) is released from the PVC backbone. This stage results in the formation of conjugated polyene sequences within the polymer structure. The second stage occurred between approximately 400 °C and 500 °C, corresponding to further decomposition of the polyene structure and formation of carbonaceous residues. The residual char yield recorded for virgin PVC was approximately 12.8 %, indicating moderate thermal stability typical of unmodified PVC systems (Rahmah *et al.,* 2017; Boraei *et al.,* 2024).

Modification of PVC with Epoxidized Soybean Oil resulted in noticeable improvement in thermal stability relative to the control sample. The ESO-containing formulations exhibited delayed onset of degradation, which is attributed to the stabilizing effect of epoxy groups. These epoxy functional groups are capable of reacting with hydrogen chloride released during thermal degradation, thereby reducing autocatalytic degradation reactions and stabilizing the polymer backbone. Similar thermal stabilization effects of ESO in PVC systems have been widely reported in literature (Rahmah *et al.,* 2017; Deshmukh and Joshi, 2014).

The incorporation of Polyvinyl Acetate also contributed to improved thermal resistance of the composite systems. The presence of ester functional groups in PVAc promotes intermolecular interactions within the polymer blend, thereby improving structural cohesion and delaying thermal degradation processes. The improved compatibility between PVC and PVAc enhances heat resistance and contributes to stabilization of the polymer matrix (Lekshmi *et al.,* 2024).

Further improvement in thermal stability was observed in composites containing Graphene Oxide. The presence of GO introduced a barrier effect within the polymer matrix, which reduced the diffusion rate of volatile degradation products and improved heat resistance. The layered structure and high thermal stability of GO also contributed to increased residual char formation during high-temperature exposure. These observations are consistent with reported behaviour of GO-reinforced polymer systems, where enhanced thermal stability is achieved through restricted chain mobility and improved heat dissipation (Kuilla *et al*., 2010; Huang *et al.,* 2024).

Among the hybrid formulations, Hybrid H1 exhibited the highest thermal stability, with a residual char yield of approximately 36 %, representing a substantial increase compared to the 12.8 % observed for virgin PVC. This improvement confirms the synergistic stabilization effect resulting from the combined presence of ESO, PVAc, and GO within the polymer matrix. The simultaneous action of epoxy stabilization, interfacial compatibility, and nanoscale reinforcement contributed to the observed enhancement in thermal resistance.

The improved thermal stability observed in hybrid systems demonstrates the effectiveness of multi-component modification in controlling degradation behaviour of PVC composites. The combined structural and chemical stabilization mechanisms introduced by ESO, PVAc, and GO significantly enhanced the resistance of the polymer matrix to thermal decomposition, thereby extending the potential service temperature range of the material.

Overall, the TGA results confirmed that hybrid modification significantly improved the thermal performance of PVC-based composites, making them suitable for applications requiring enhanced thermal durability and resistance to thermal degradation.

CONCLUSION

The mechanical and thermal performance of PVC-based composites modified with PVAc, ESO, and GO was successfully evaluated. The results demonstrated that modifier type and concentration significantly influenced the mechanical behaviour of the composites. ESO-modified systems exhibited notable improvement in tensile strength and elongation at optimal loading levels, while excessive plasticizer addition resulted in reduced strength. PVAc incorporation enhanced flexibility, whereas GO addition contributed to improved reinforcement and stiffness characteristics. Hybrid composites displayed the most balanced mechanical performance, indicating synergistic interactions among the incorporated modifiers. One-way ANOVA analysis showed statistically significant differences among tensile strength values of the modified composites (F = 16.97, $p < 0.05$), confirming that modifier composition plays a critical role in determining mechanical performance. These findings validate the effectiveness of hybrid modification strategies and demonstrate their suitability for improving the structural performance of PVC-based composite materials.

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