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Experimental and Correlative Analysis of Viscosity, Surface Tension, and Rheological Properties Influencing E-Liquid Leakage

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Abstract

The increasing use of e-cigarettes underscores the importance of understanding the physicochemical properties of e-liquids—particularly viscosity, surface tension, and rheological behavior—as these parameters influence leakage performance and user experience. This study evaluated the interrelationship among viscosity, surface tension, and storage modulus (G') across PG, VG, water, and standardized PG/VG mixtures, and examined how these properties contribute to leakage tendencies under controlled thermal and vacuum conditions. Surface-tension values ranged from 37 mN/m (PG) to 64 mN/m (VG), with PG/VG blends predominantly falling within a moderate intermediate range (39 - 47 mN/m), aside from two deviations at 90:10 (54.24 mN/m) and 50:50 (42.82 mN/m). Conversely, viscosity and G' increased consistently with VG content, strongly reducing leakage risk, while PG-rich blends demonstrated lower viscoelasticity and higher leakage susceptibility. These findings indicate that viscosity and elasticity are the primary determinants of leakage, whereas surface tension plays a secondary role. The work provides a quantitative foundation for optimizing PG/VG ratios in commercial e-liquid formulations to enhance device reliability.

Keywords

E-Liquids, Propylene Glycol (PG), Vegetable Glycerin (VG), Leakage, Formulation

1. Introduction

The comprehensive characterization of e-liquids necessitates a meticulous examination of their rheological properties, with a particular focus on viscosity, surface tension, and storage modulus, all of which intricately govern their behaviour [1]. Viscosity, a measure of a fluid's resistance to flow, plays a crucial role in determining the ease with which an e-liquid can be vaporized and delivered to the user [2]. Surface tension, on the other hand, influences the formation of droplets and the wetting behaviour of the e-liquid on the heating element, thereby affecting the efficiency of vaporization and the overall aerosol characteristics [3]. The storage modulus, a key indicator of a material's elastic properties, provides insights into the ability of an e-liquid to store energy and resist deformation, which is particularly relevant in understanding its behaviour under the dynamic conditions of vaping [4]. Understanding the interplay of these factors is crucial for optimizing e-liquid formulations, improving device performance, and ensuring a consistent and satisfying vaping experience.

The viscoelastic properties of materials can be probed through various methods, including stress relaxation tests and creep tests, allowing for the determination of characteristic relaxation times and specific material constants [5]. The intricate relationship between viscosity and elasticity in e-liquids can be further elucidated by considering their behaviour under different shear rates and temperatures. An increase in temperature typically leads to a decrease in viscosity, affecting the flow properties and vaporization dynamics of the e-liquid [6]. Furthermore, the addition of certain compounds or polymers can modify the viscoelastic behaviour, enabling the fine-tuning of e-liquid properties for specific applications. By manipulating the composition and physical conditions, it is possible to engineer e-liquids with tailored rheological properties, optimizing their performance and user experience [3]. In addition to traditional rheological measurements, advanced techniques like piezo tromboelastography, molecular dynamics simulations, and ultrasonic spectroscopy can provide deeper insights into the viscoelastic properties of e-liquids [2]. The examination of mechanical state diagrams can further illuminate the transitions between fluid-like and solid-like behaviors, offering a comprehensive understanding of the material's response to external forces [7].

Characterizing the viscoelastic behavior of e-liquids is of utmost importance, particularly given their time-dependent response to applied forces [8]. This characterization typically involves the determination of parameters like storage modulus, loss modulus, and viscosity, which collectively define the material's printability and performance [4]. By carefully controlling the composition and environmental conditions, it is possible to tailor the rheological properties of e-liquids to meet specific application requirements, ensuring optimal performance and stability. The viscous and elastic moduli can be measured as a function of temperature to unambiguously assign the rheological changes associated with the sol-gel transition [9]. These factors contribute significantly to the perceived quality and satisfaction associated with vaping, highlighting the importance of rheological considerations in e-liquid design. Rheometry and suitable rheological models play a crucial role in evaluating rheological characteristics in various fields, including polymers, biology, food processing, and dispersion systems [10].

The study of complex fluids, including e-liquids, has benefited significantly from advancements in microfluidic devices, which allow for precise control of flow and channel geometry, enabling high-throughput analysis and integration of flow visualization techniques. Microfluidic viscometers offer unique capabilities for characterizing the rheological properties of small volumes of fluids under controlled conditions [11]. Understanding the flow behaviour of complex fluids, such as polymer solutions and suspensions, is crucial in various industrial processes, including hydraulic fracturing and polymer composite processing [12]. Rheological measurements are essential for characterizing the flow and deformation of materials, aiding in the optimization of rheological parameters. These parameters influence the stability, texture, consistency, and bioavailability of pharmaceutical formulations, cosmetics, and foodstuffs [13].

The growing popularity of e-cigarettes has led to a surge in research and development efforts to improve their performance and safety [14]. One of the critical aspects of e-cigarette performance is the behaviour of e-liquid, which is responsible for delivering the desired flavor and nicotine to the user. Leakage of e-liquids from devices is a common issue that can negatively impact the user experience and potentially expose users to undesirable exposures [11] [14]. The viscosity, surface tension, and rheological properties of the e-liquid are believed to play a crucial role in the leakage behaviour. Viscosity is known to affect the flow characteristics of the e-liquid, with a higher viscosity potentially reducing the likelihood of leakage. On the other hand, surface tension influences the ability of the e-liquid to wet and spread on surfaces, which can affect its tendency to seep through small openings or gaps in the e-cigarette device [15].

Finally, the rheological G' value, which represents the elastic or solid-like behavior of the e-liquid, can also contribute to its leakage behavior, as a higher G' value may indicate greater resistance to flow and deformation. E-liquids are complex mixtures, and their properties can be influenced by a multitude of factors. Understanding these interdependencies could lead to more effective strategies for mitigating leakage and enhancing the overall quality of e-cigarette products [16]. Ultimately, the goal of this study is to provide valuable insights that can contribute to the development of safer, more reliable, and more enjoyable e-cigarette experiences for users.

The evolution of e-cigarette technology has brought attention to the formulation of e-liquids, particularly concerning their physicochemical properties that affect device functionality and user experience. Leakage remains a prevalent issue, often resulting from suboptimal interactions among viscosity, surface tension, and rheological properties.

Understanding the correlations among these properties is essential for formulating e-liquids that minimize leakage and optimize performance. This study investigates these relationships across various PG/VG ratios and commercial formulations to inform better product development strategies.

2. Materials and Methods

2.1. Preparation of Standard Formulations

Seven binary mixtures of propylene glycol (PG) and vegetable glycerin (VG) were prepared in volumetric ratios of 30:70, 40:60, 50:50, 60:40, 70:30, 80:20, and 90:10 (PG:VG, % v/v), along with pure PG and VG. These served as reference standards for the comparative evaluation of the physicochemical properties.

2.2. Experimental Conditions

All analyses were performed under controlled laboratory conditions at 20 ± 0.5˚C to ensure reproducibility.

2.2.1. Rheological Measurements (Storage Modulus, G')

The elastic behavior was assessed using an Anton Paar MCR302 Rheometer (Anton Paar GmbH, Austria). The storage modulus (G'), indicative of viscoelasticity, was recorded after instrument calibration following the manufacturer's guidelines. Measurements were conducted at 20˚C using a cone-and-plate geometry (CP50; 49 mm, 0.994˚), with a fixed gap of 0.101 mm. Oscillatory tests employed a strain amplitude of 10%, which was verified to fall within the LVR for all formulations, at a frequency of 1 Hz. The G' values provided represent the time-averaged storage modulus obtained over a 300 s time sweep

2.2.2. Viscosity Assessment

Viscosity measurements were performed using a Brookfield DV2T viscometer (Brookfield Engineering Laboratories, USA) equipped with an SC4-18 spindle and the SC4-13RP small-sample chamber. All measurements were conducted at 20˚C. The viscosity of each formulation was recorded at a controlled shear rate of 6.6001 s^{-1} (corresponding to the instrument-defined rotational speed). As only a single shear rate was tested and no additional rpm/shear-rate sweep was performed, shear-rate dependence could not be fully assessed. However, the readings remained stable over the measurement period, and the fluids were therefore treated as effectively Newtonian under the specific measurement conditions. Reported values correspond to the steady-state viscosity after signal stabilisation.

2.2.3. Surface Tension Measurement

Surface tension was determined using a KRÜSS 100C Force Tensiometer (KRÜSS GmbH, Germany). Calibration was performed before each session using deionized water as a reference. All measurements were performed at 20˚C.

2.2.4. Selection and Characterization of Commercial E-Liquids

A total of 80 commercially available e-liquids, encompassing a diverse range of flavour categories (e.g., fruit-based, tobacco-based), were selected for analysis. Each sample underwent physical characterization—including viscosity, surface tension, and storage modulus (G')—following the same methodologies applied to the standard formulations.

2.2.5. Data Analysis

Comparative analysis between commercial e-liquids and PG/VG standards was performed to identify deviations in the physical behavior. The samples were grouped based on their proximity to the reference values. Correlation analysis of viscosity, surface tension, and G' was conducted to explore the interdependencies and potential implications for aerosol generation and user experience.

2.2.6. Leakage Testing for the Standard Formulation

Based on the rheological and viscosity profiles, four PG/VG ratios (70:30, 60:40, 40:60, and 30:70) were selected for leakage testing under thermal and pressure conditions. Ten pods per formulation were tested, and the average pass rates were recorded to evaluate the leakage resistance.

2.3. Results

2.3.1. Viscosity Analysis of Standard Formulations

Viscosity measurements revealed a strong dependence on the VG concentration. Pure VG exhibited the highest viscosity (>1,400 mPa·s), confirming its inherently thick nature, whereas pure PG and deionized water showed markedly lower values (~100 mPa·s) (Figure 1). Among the binary mixtures, formulations with higher VG content (70:30 and 60:40 (VG: PG)) displayed elevated viscosities of approximately 550 mPa·s and 400 mPa·s, respectively. An increase in the PG proportion resulted in a progressive decline in viscosity, with the 90:10 PG:VG blend approaching the viscosity of pure PG.

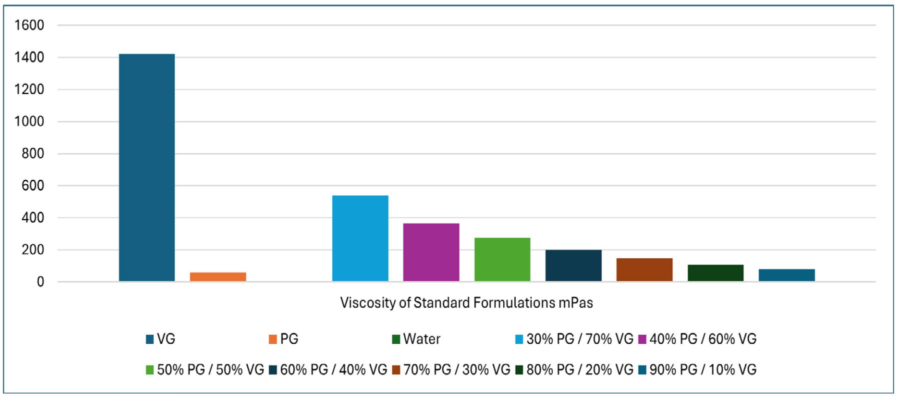

Figure 1. Viscosity analysis of different ratios of the standard formulations mPa·s.

2.3.2. Rheological Characterization of Standard Formulations

Figure 2 illustrates the variation in the storage modulus (G') across the PG/VG ratios. Pure VG exhibited the highest G' (~0.0135 Pa), indicating pronounced elasticity and structural integrity. In contrast, pure PG and water recorded negligible values, reflecting their minimal elastic behavior. Mixtures with higher VG content (30:70 and 40:60 PG:VG) demonstrated intermediate G' values (~0.007 Pa and 0.006 Pa), while formulations richer in PG (≥50%) showed a steady decline, with 90:10 PG:VG approaching near-zero elasticity.

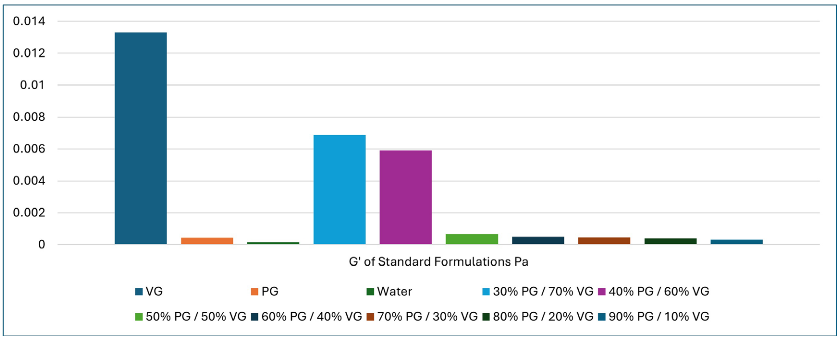

Figure 2. This graph represents the G' value obtained for different ratios of the Standard formulation Pa in Anton Paar Rheometer.

2.3.3. Surface Tension Analysis of Standard Formulations

Surface-tension values (Figure 3) ranged from 37.01 mN/m for pure PG to 64 mN/m for pure VG, with water showing the highest value (72.7 mN/m). The PG/VG mixtures demonstrated intermediate values, typically between 39.1 and 46.9 mN/m, consistent with expected mixing behavior (Table 1). Two deviations were observed: the 90:10 PG/VG blend showed a moderately elevated surface tension (54.24 mN/m), and the 50:50 PG/VG blend measured 42.82 mN/m, aligning with midpoint expectations rather than previously reported higher values. This indicates that surface tension varies moderately across formulations but remains secondary to viscosity and elasticity in influencing leakage tendencies.

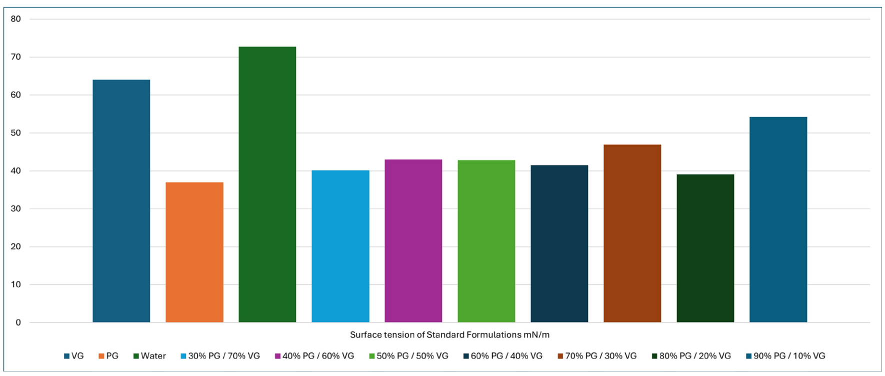

Figure 3. Surface tension analysis of different ratios of the standard formulations mN/m.

Table 1. Viscosity, rheological G' and Surface tension of different standard formulations.

Percentage of formulation	Viscosity of Standard Formulations mPa·s	G' of Standard Formulations Pa	Surface tension of Standard Formulations mN/m
VG	1421.9	0.01331	64
PG	59.172	0.00043	37.01
Water	1.0067	0.00014	72.7
30% PG/70% VG	437.9	0.00687	40.11
40% PG/60% VG	326.64	0.00654	43.01
50% PG/50% VG	275.53	0.00589	42.82

Continued

60% PG/40% VG	198.18	0.00051	41.46
70% PG/30% VG	146.15	0.00045	46.91
80% PG/20% VG	108.76	0.00040	39.1
90% PG/10% VG	79.485	0.00031	54.24

2.3.4. Correlation of Viscosity, G' Value of Different E-Liquids to the Standard Formulation

Figure 4 shows that e-liquids with higher VG content (≥60%) exhibited viscosities between 220 and 380 mPa·s, aligning with high-VG standard formulations. Started by screening 80 different commercial e-liquids in the lab. However, only 29 of them contained the required nicotine strength of 20 mg/mL, which was essential for ensuring consistency with our standard formulation (Table 2). Any product with a nicotine concentration either below or above 20 mg/mL was excluded. This exclusion also removed all samples that did not accurately meet their labeled nicotine claims. After applying these criteria, 29 formulations remained, and proceeded to test for viscosity, rheological properties, and leakage behavior., Figure 5 demonstrates that high-PG, low-VG formulations (40% - 20% VG) exhibited significantly lower viscosity (100 - 180 mPa·s) and G' values, indicating reduced elasticity and greater fluidity (Table 3). Such formulations are more prone to leakage because of insufficient structural resistance.

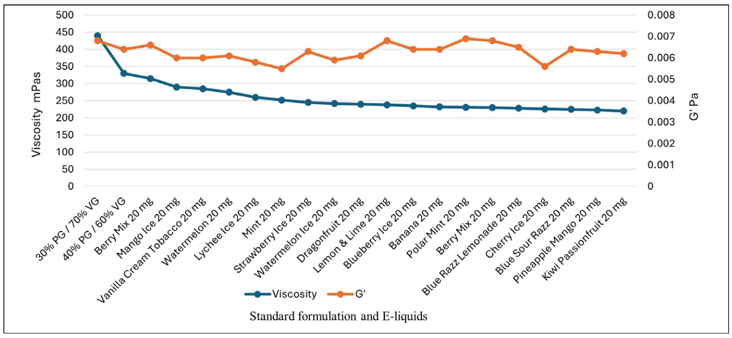

Figure 4. Dual-axis plot showing viscosity and G' values across e-liquids to the high VG and Low PG standard formulation.

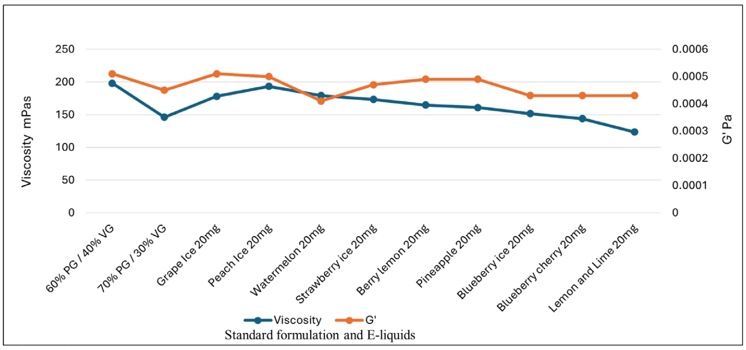

Figure 5. Dual-axis plot showing viscosity and G' values across e-liquids to the high PG and Low VG standard formulation.

Table 2. Correlation of viscosity, G' value of High VG and Low PG standard formulation and different e-liquids.

Percentage of formulation	Viscosity of Standard Formulations mPa·s	G' of Standard Formulations Pa
30% PG/70% VG	437.9	0.00687
40% PG/60% VG	326.64	0.00654
E-Liquids	**Viscosity**	**G' e-liquids**
Berry Mix 20 mg	316.88	0.0069
Mango Ice 20 mg	287.9	0.0066
Vanilla Cream Tobacco 20 mg	286.58	0.0068
Watermelon 20 mg	282.03	0.0059
Lychee ice 20 mg	256.92	0.0059
Mint 20 mg	250.91	0.0061
Strawberry Ice 20 mg	243.44	0.0063
Watermelon Ice 20 mg	241.68	0.0059
Dragon fruit 20 mg	239.59	0.0061
Lemon and Lime 20 mg	236.88	0.0070
Blueberry Ice 20 mg	232.74	0.0065
Banana Ice 20 mg	230.03	0.0065
Polar Menthol 20 mg	230.73	0.0072
Berry Mix 20 mg	227.78	0.0071
Blue Razz Lemonade 20 mg	225.43	0.0065
Cherry Ice 20 mg	224.81	0.0055
Blue sour Razz 20 mg	223.54	0.0064
Triple Melon 20 mg	221.1	0.0064
Kiwi Passionfruit 20 mg	219.37	0.0064

2.3.5. Correlation Analysis

A correlation analysis was performed to quantify the relationship between viscosity and viscoelastic properties across the standard formulations and the 29 commercial e-liquids included in the study. Viscosity and G' demonstrated a strong, statistically significant positive correlation (Pearson's $r = 0.755$, $p = 3.89\ x^{-7}$, $n = 18$; 95% CI: 0.55 - 0.87), indicating that formulations with higher viscosity also exhibited greater elastic structure. This correlation aligns with observed leakage patterns. Within the high VG subset (Table 3), the association was weak and not significant ($r = 0.243$, $p = 0.288$, $n = 18$), consistent with the limited dynamic range in both parameters in VG-rich blends. Where VG-rich, high-viscosity blends showed reduced leakage, low-viscosity, PG-rich blends showed a correlation ($r = 0.543$, $p = 0.068$, $n = 11$), indicating substantially weaker structural resistance and higher leakage. Surface tension was not correlated with either viscosity or leakage (ρ values between −0.10 and 0.20, $p > 0.40$), reinforcing its secondary role in leakage behaviour.

Table 3. Correlation of viscosity, G' value of High PG and Low VG standard formulation, and different e-liquids.

Percentage of Formulation	Viscosity of Standard Formulations mPa·s	G' of Standard Formulations Pa
60% PG/40% VG	198.18	0.00051
70% PG/30% VG	146.15	0.00045
E-Liquids	**Viscosity**	**G' e-Liquids**
Grape Ice 20 mg	178.18	0.00051
Peach Ice 20 mg	193.37	0.0005
Watermelon 20 mg	179.33	0.00041
Strawberry Ice 20 mg	173.36	0.00047
Berry Lemon 20 mg	164.65	0.00049
Pineapple 20 mg	160.91	0.00049
Blueberry Ice 20 mg	151.5	0.00043
Blueberry Cherry 20 mg	143.85	0.00043
Lemon and Lime 20 mg	123.55	0.00043
Peach Ice 18 mg	96.7	0.00045

2.3.6. Leakage Testing of the Standard Formulation

Leakage performance varied markedly across the PG/VG ratios (Figure 6). Formulations with higher VG contents (70:30 and 60:40) achieved pass rates of 100% and 70%, respectively, under thermal and vacuum conditions. In contrast, 40:60 VG:PG showed moderate resistance (50%), while 30:70 VG:PG exhibited only 10%, indicating high leakage susceptibility. These findings suggest that elevated VG levels, associated with higher viscosity and G', significantly reduce the leakage risk compared to PG-rich blends.

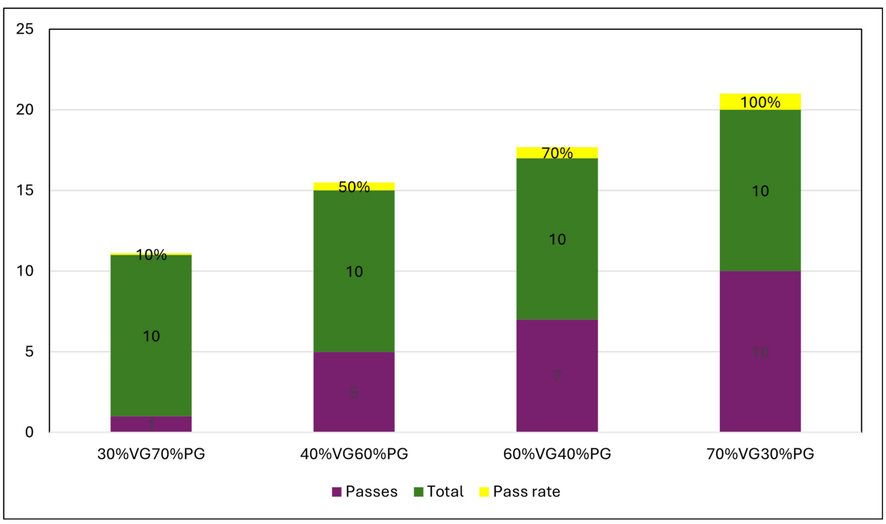

Figure 6. Leakage pass rate by VG/PG ratio in formulations.

2.4. Discussion

This study provides a comprehensive evaluation of the viscosity, surface tension, and rheological properties of standard PG/VG formulations, offering insights into their influence on e-liquid performance and leakage behavior. Previous research has highlighted the importance of viscoelasticity and interfacial tension in optimizing formulations for pharmaceuticals, cosmetics, and other industrial applications, as these properties govern their structural integrity and functional stability. Similar principles apply to e-liquids, where the rheological behavior directly impacts the device reliability and user experience.

Viscosity and Rheological Trends: Our findings confirmed that the VG concentration is a primary determinant of viscosity. Pure VG exhibited markedly high viscosity (>1,400 mPa·s), whereas PG and water showed significantly lower values (~100 mPa·s), consistent with the established rheological differences. Mixtures with higher VG ratios (70:30 and 60:40 VG:PG) demonstrated elevated viscosities (~550 and ~400 mPa·s), whereas PG-rich blends exhibited progressively lower values. Since viscosity influences wicking and aerosol generation in ENDS, maintaining an optimal range is critical; excessively low viscosity may increase the risk of leakage, whereas excessively high viscosity may impair vaporization efficiency.

Rheological Behaviour: Storage modulus (G') measurements revealed a similar trend. Pure VG displayed the highest G' (~0.0135 Pa), indicating strong elastic behavior, whereas PG and water approached zero, reflecting Newtonian characteristics. Formulations with a higher VG content exhibited intermediate G' values, confirming VG's role of VG in enhancing viscoelasticity. Increased PG proportion reduced elasticity, correlating with greater leakage susceptibility due to diminished structural resistance.

Surface Tension Behaviour: Surface-tension behavior across PG, VG, and their mixtures followed expected physicochemical trends and exhibited only moderate variation. PG showed the lowest surface tension (37.01 mN/m), VG demonstrated higher values (64 mN/m), and water remained the highest (72.7 mN/m). Most PG/VG mixtures fell within an intermediate range of 39.1 - 46.9 mN/m, reflecting predictable mixing effects across compositions. A modest deviation was observed in the 90:10 PG/VG blend, which exhibited an elevated surface tension (54.24 mN/m), suggesting mild non-linear interactions at extreme formulation ratios. Despite these variations, surface tension exerted comparatively little influence on leakage performance. In contrast, viscosity and viscoelasticity (G') showed strong and systematic relationships with leakage behavior. VG-rich formulations displayed substantially higher viscosity and greater elastic structure, enabling improved resistance to leakage under thermal and vacuum stress conditions. PG-dominant formulations, with much lower viscosity and G' values, lacked sufficient structural cohesion and were therefore more prone to leakage. These patterns were consistent across both the controlled PG/VG mixtures and the screened commercial e-liquids, reinforcing the central role of rheological properties in governing leakage.

Correlation of Viscosity and Rheology G' in Leakage Issues:

Furthermore, when comparing the rheological behaviour, a positive correlation is evident between viscosity and the elastic modulus (G'). According to [17], cream and gel products exhibit viscoelastic properties characterized by high viscosity and a high storage modulus (G'), which play a significant role in enhancing product stability and ease of application. The same pattern was also observed in the results, that as viscosity increases, the G' value also rises, indicating enhanced viscoelastic behaviour, and both are directly proportional to each other. Viscoelasticity is a desirable property in e-liquids, as it allows the liquid to maintain structural integrity under mechanical stress, thereby reducing the likelihood of leakage. This was substantiated by [18] that elastomeric seals with viscoelastic properties exhibit much less creep and extrusion into gaps under pressure, compared to non-viscoelastic materials. This enhanced resistance directly correlates with improved sealing performance and reduced leakage.

The leakage result showed that high VG showed a higher leakage pass rate. These findings align with existing literature (**PMC**), Viscosity is directly proportional to G' in the standard formulations, indicating that higher VG concentrations contribute to increased viscosity and elasticity in e-liquid formulations, thereby potentially reducing leakage by enhancing structural stability. Together, these findings demonstrate that higher VG concentrations not only increase viscosity but also enhance the elastic (G') response of the liquid. This correlation suggests that optimizing VG content in e-liquid formulations can improve viscoelastic properties, contributing to better performance and may reduce leakage issues in vaping devices.

Correlation analysis confirmed that viscosity and G' are tightly linked, with higher viscosity strongly associated with increased elastic structure ($r = 0.75$). G' rises in tandem, consistent with enhanced network-like structuring in VG-rich formulations. In contrast, surface tension showed no meaningful correlation with leakage or rheological properties, underscoring its comparatively minor contribution to leakage behaviour.

2.5. Conclusions

Collectively, these findings emphasize the critical role of VG in enhancing both the viscoelastic (G') and viscous properties of e-liquid formulations. Higher VG concentrations confer greater structural integrity and elasticity, which can mitigate leakage and improve device reliability, whereas high PG content leads to lower viscosity and elasticity, raising the potential for leakage. However, excessively high viscosity may impair wicking and aerosolization, requiring a balance tailored to the specific device design. Additionally, non-linear surface tension behaviours highlight the complexity of intermolecular interactions in binary PG/VG systems, underscoring the need for empirical formulation rather than simple additive models.

In conclusion, optimizing the PG/VG ratio is essential for achieving a desirable balance of viscosity, elasticity, and surface tension in e-liquid formulations. These insights are vital for guiding formulation strategies to ensure consistent performance, improved user experience, and product safety in ENDS applications.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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