

Tropical weathering of commercial fuels: Implications for evaporation kinetics, vapor generation, and energy degradation

Muhammad Aliff Ikhmal Zulkafli^{a,*}, Muhammad Abdullah^b, Mohd Zahirasri Mohd Tohir^a, Mohamad Syazarudin Md Said^{a,*}

^a Safety Engineering Interest Group, Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia

^b Department of Mechanical and Aerospace Engineering, Kuliyyah of Engineering, International Islamic University Malaysia

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ABSTRACT

The extended stockpiling of liquid vehicle fuels necessitates an understanding of their physicochemical degradation behaviors under ambient tropical conditions. This study investigates the long-term volatility, rheological shifts, and thermodynamic degradation of commercial vehicle fuels, specifically RON95, RON97, and ultra-low-sulfur diesel subjected to a 130-day ambient weathering period. Characterizations were performed utilizing gravimetric monitoring, rotational viscometry, gas chromatography–flame ionization detection (GC-FID), and bomb calorimetry.

The results demonstrated that prolonged atmospheric exposure altered fuel properties through light component evaporation. Over a 130-day storage period, RON95 exhibited the highest total mass loss at 79.32%, followed by RON97 at 75.00%, while Diesel displayed high stability with only a 1.30% loss. Viscosity increased across all samples due to the concentration of residual heavy hydrocarbons, with RON97 undergoing the largest increase (2.699 to 3.748 mPa.s), compared to RON95 (2.549 to 3.448 mPa.s) and Diesel (10.04 to 10.66 mPa.s). GC-FID confirmed varying reductions in light volatile fractions. Furthermore, 70 days of prolonged storage led to calorific value degradation across all samples, driven by light component loss. RON95 suffered the largest energy reduction (12.1%), followed by RON97 (6.0%) and Diesel (4.9%).

1. Introduction

Recent disruptions in global energy supply chains, particularly the 2026 constraints on maritime transport through the Strait of Hormuz, have intensified concerns regarding fuel security in Asia [1,2]. In response, many Southeast Asian countries have expanded strategic fuel reserves and extended the storage duration of commercial transportation fuels. While these measures can improve energy security in the short term, they also create an important challenge. Liquid fuels may gradually degrade when stored for a long period under normal ambient conditions.

During storage, liquid fuels are subject to continuous evaporation of volatile organic compounds (VOCs), leading to the emission of hazardous air pollutants (HAPs) and progressive alteration of fuel composition

[3,4]. The loss of lighter hydrocarbons causes the remaining fuel to contain a higher proportion of heavier components. This gradual change can affect important fuel properties, such as vapor pressure, viscosity, and calorific value [5,6]. These changes can adversely affect fuel atomization, combustion efficiency, and engine performance. In addition, evolving vapor composition and emission rates may influence vapor cloud formation and associated fire hazards during storage and handling operations [7].

Fuel evaporation in open or semi-confined environments is governed by multicomponent vapor–liquid equilibrium, diffusion-controlled mass transfer, and ambient thermodynamic conditions. Previous studies have demonstrated that gasoline evaporation follows non-linear, time-dependent behavior due to the coupled effects of compositional evolution and decreasing vapor pressure [8,9]. However, previous studies on

Abbreviations: CV, Calorific value; FID, Flame Ionization Detector; GC, Gas Chromatograph / Gas Chromatography; GC-FID, Gas Chromatography–Flame Ionization Detection; HAPs, Hazardous Air Pollutants; IEA, International Energy Agency; RON, Research Octane Number (used in RON95, RON97); ULSD, Ultra-Low-Sulfur Diesel; VOCs, Volatile Organic Compounds.

* Corresponding author.

E-mail address: syazarudin@upm.edu.my (M.S. Md Said).

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fuel degradation reported generic gasoline mixtures without clearly specifying the Research Octane Number (RON) or the commercial fuel formulation. As commercial fuels with different octane ratings, such as RON95 and RON97, may contain different proportions of light hydrocarbon fractions and additive packages, their evaporative behavior and associated energy loss may not be identical.

In addition, existing empirical models may not account for the ambient thermodynamic conditions associated with tropical environments. Equatorial climates are generally characterized by relatively high temperatures and fluctuations in relative humidity, which may influence the long-term storage stability of fuels. This consideration may be particularly relevant under tropical conditions, where elevated temperatures and variations in humidity could affect evaporation behavior and, consequently, the stability of stored fuels [10]. Therefore, there remains a gap in understanding how commercially available Southeast Asian fuels, particularly RON95, RON97, and ultra-low-sulfur diesel (ULSD), may undergo physical, chemical, and energy-related changes during prolonged storage under ambient tropical conditions.

The purposes of this study are to determine the evaporation rate and mass loss of the fuels under tropical ambient conditions. The study also aims to examine changes in the fuel rheological properties and composition during storage. In addition, the effect of prolonged evaporation on the gross calorific value of the fuels will be evaluated. By integrating gravimetric analysis, rotational viscometry, gas chromatography–flame ionization detection (GC-FID), and bomb calorimetry, this study evaluates fuel degradation behavior and their implications for storage stability and performance.

The findings provide region-specific empirical data and further insight into the weathering behavior of multicomponent fuels. These results may help improve the prediction of fuel evaporation and provide useful information for developing safer and more efficient fuel storage practices under tropical conditions.

2. Materials and methods

2.1. Materials and sample preparation

Three commercial-grade vehicle fuels, unleaded RON95 gasoline, unleaded RON97 gasoline, and ultra-low-sulfur diesel (ULSD) were utilized in this study to investigate volatility and flammability variations under prolonged ambient storage. All fuel samples were procured directly from a commercial service station located in Serdang, Selangor, Malaysia, ensuring representative domestic fuel compositions.

To simulate prolonged, semi-open storage weathering representative of tropical environmental conditions, the fuel samples were transferred into identical, unsealed glass vessels. The samples were continuously exposed to ambient laboratory environments (housed within an inactive, unsealed fume hood to mimic depot ventilation while preventing direct particulate contamination) for a maximum observation period of 130 days. Daily environmental parameters, including ambient temperature and relative humidity, were continuously monitored.

2.2. Gravimetric analysis of fuel evaporation

The macroscopic evaporation kinetics and time-dependent mass loss of each fuel were quantified gravimetrically. An electronic precision balance was employed to record the mass of the fuel samples at regular intervals over the 130-day weathering period. The daily evaporated fraction, representing the cumulative percentage of mass lost to the atmosphere, was calculated using the following equation:

$$\text{Weight loss fractions} = \frac{w_0 - w}{w_0 - w_b}$$

where w_0 represents the initial combined mass of the glass vessel and the fuel, w is the total mass of the vessel and residual fuel at sampling time t ,

and w_b denotes the tare mass of the empty glass vessel.

2.3. Rheological characterization

To evaluate the impact of light-hydrocarbon evaporation on the macroscopic fluid mechanics of the residual fuel, viscosity was measured using an Anton Paar ViscoQC™ 100 rotational viscometer. Given the inherently low initial viscosity of volatile hydrocarbons, the viscometer was configured to a high-shear rotational speed to ensure measurement sensitivity and torque stabilization.

Rheological parameters, specifically dynamic viscosity (mPa.s) and rotational torque (%), were recorded for each sample over a 60-day monitoring window. Each sample was measured for a minimum duration of 5 min under ambient laboratory conditions. No active thermal control was applied to the fuel samples during the rheological measurements. This may represent an important limitation of the study, as variations in ambient temperature could have influenced the measured rheological properties.

2.4. Chromatographic speciation of weathering components (GC-FID)

The dynamic shift in multi-component hydrocarbon profiles was analytically resolved using an Agilent 7890A Gas Chromatograph equipped with dual Flame Ionization Detectors (GC-FID). To ensure high-resolution speciation of both aliphatic and aromatic fractions, a dual-column configuration was utilized: an HP-5 silica-fused capillary column was deployed for general hydrocarbon constituent separation, while an aluminum oxide silica-fused capillary column specifically resolved aromatic hydrocarbons.

Sample aliquots of 1 mL were introduced via an automated liquid sampler. High-purity hydrogen served as the carrier gas, maintained at a constant volumetric flow rate of 25 mL/min. The GC oven temperature profile was rigorously programmed to optimize component resolution: an initial hold at 50 °C for 2 min, followed by a primary heating ramp of 5 °C/min to 160 °C, and a secondary accelerated ramp of 20 °C/min to a final isothermal hold at 250 °C for 5 min. The injector port and FID temperatures were maintained at 250 °C and 230 °C, respectively.

2.5. Gross calorific value determination

To quantify the degradation in energy content resulting from continuous hydrocarbon volatilization, the gross calorific value (heat of combustion) of both the baseline (fresh) and the prolonged-storage (weathered) fuels was measured using a RAP145A Oxygen Bomb Calorimeter. Sample aliquots were weighed, sealed within the oxygen-pressurized bomb crucible, and electrically ignited via a standardized fuse wire. The total energy released during combustion was determined by measuring the temperature rise of the surrounding water bath, incorporating standard thermochemical corrections for fuse wire combustion and acid formation.

3. Results and discussion

3.1. Evaporation kinetics and mass loss behavior

The macroscopic weathering and mass loss trajectories of the fuel samples were continuously monitored over a 130-day storage period. As shown in Fig. 1, the weight loss for the unleaded gasolines (RON95 and RON97) exhibited higher declines during the first 10 days, indicating the active evaporation of light hydrocarbons. From the 11th to the 51st day, the weight loss activity began to exhibit slower declines, with differences of 64.1 g for RON95 and 60.5 g for RON97. A significant weight drop was observed between the 52nd and 58th days, which correlated with a considerable change in environmental conditions. Over the entire 130-day period, the mass of RON95 decreased drastically from 351.5 g to 72.7 g, while RON97 decreased from 364.6 g to 89.8 g. In contrast,

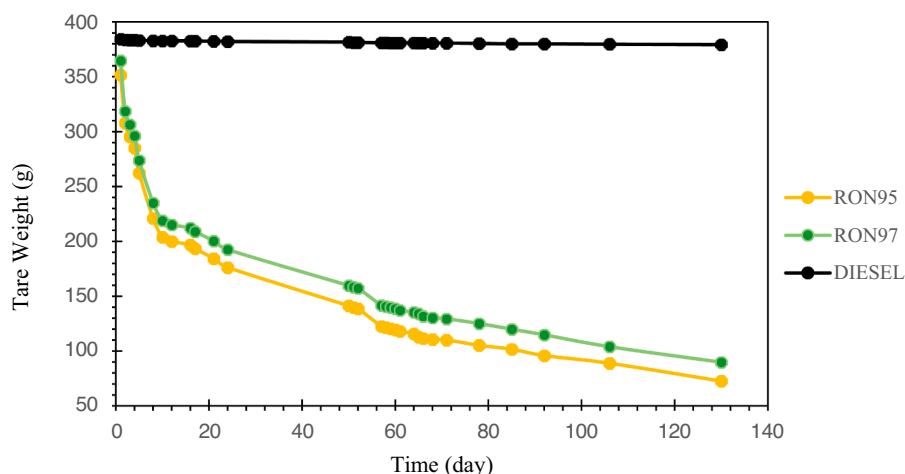


Fig. 1. Weight change vs. time.

Diesel demonstrated the slowest evaporation rate, losing only 5 g (from 384.3 g to 379.3 g). This minimal loss is attributed to Diesel's composition of longer carbon chains.

The ambient thermodynamics significantly governed these evaporation kinetics. As shown in Fig. 2, increases in environmental temperature accelerated the evaporation rate because more fuel molecules gained sufficient kinetic energy to break away from the liquid surface and form vapor. Lower relative humidity was associated with accelerated evaporation, as drier atmospheric conditions can enhance the vapor concentration gradient between the fuel surface and the surrounding air.

Table 1 summarizes the cumulative evaporated fraction data. By Day 25, RON95 and RON97 had already lost 50% and 47% of their mass, respectively, compared to a mere 0.55% for Diesel. By the final 130th day, the evaporated fractions reached 79% for RON95, 75% for RON97, and 1.30% for Diesel. To develop a predictive model, these mass loss data were fitted to a logarithmic decay function (Fig. 3). The regression analysis yielded an R^2 of 0.9922 for RON95, 0.9916 for RON97, and 0.9256 for Diesel. This logarithmic behavior occurs because the fuels consist of various volatile organic compounds evaporating simultaneously in overlapping linear patterns.

3.2. Rheological transitions during prolonged storage

The continuous depletion of light hydrocarbons altered the flow characteristics of the residual fuels. Fuel viscosity was monitored

Table 1

Evaporated fraction activity of fuels during storage period.

Observation Day	Residual Mass (g)			Evaporated Fraction (%)		
	RON95	RON97	Diesel	RON95	RON97	Diesel
Day 1 (initial)	351.5	364.6	384.3	0	0	0
Day 25	176.2	192.5	382.2	50	47	0.55
Day 50	141.3	159.7	381.6	60	56	0.70
Day 75	105.3	125.1	380.4	70	66	1.01
Day 130 (final)	72.7	89.8	379.3	79	75	1.30

throughout the 60-day experimental period, as presented in Fig. 4. RON95 exhibited a noticeable increase in viscosity, rising from an initial value of 2.549 mPa·s to 3.448 mPa·s at the end of the experiment. A more pronounced change was observed for RON97, which increased from 2.699 mPa·s to 3.748 mPa·s, representing the highest overall increase among the fuels investigated. In contrast, diesel showed only a marginal increase in viscosity, from 10.04 mPa·s to 10.66 mPa·s, indicating a comparatively greater resistance to compositional changes induced by the evaporation of lighter hydrocarbon fractions. The relatively small temperature difference of 0.8 °C between Day 1 (30.1 °C) and Day 60 (29.3 °C) is unlikely to fully account for the substantial increases in viscosity observed at the macroscopic level. These findings therefore suggest that changes in fuel composition associated with evaporation may have been the primary factor contributing to the

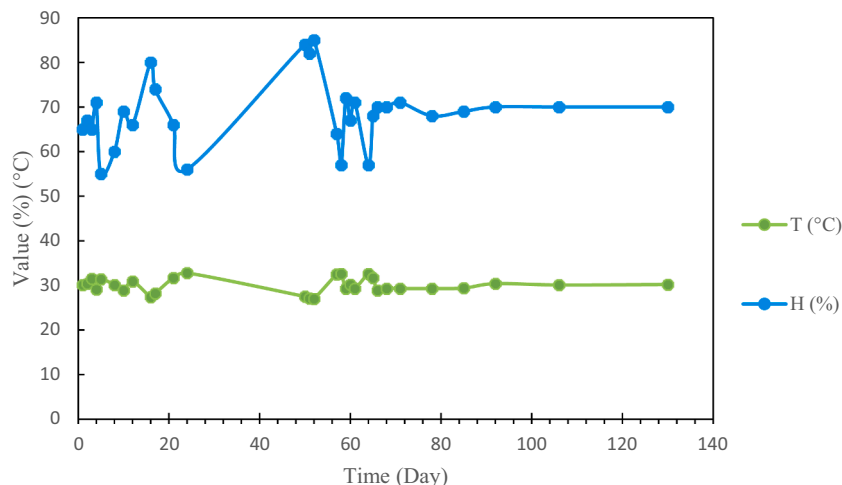


Fig. 2. Temperature and humidity vs. time.

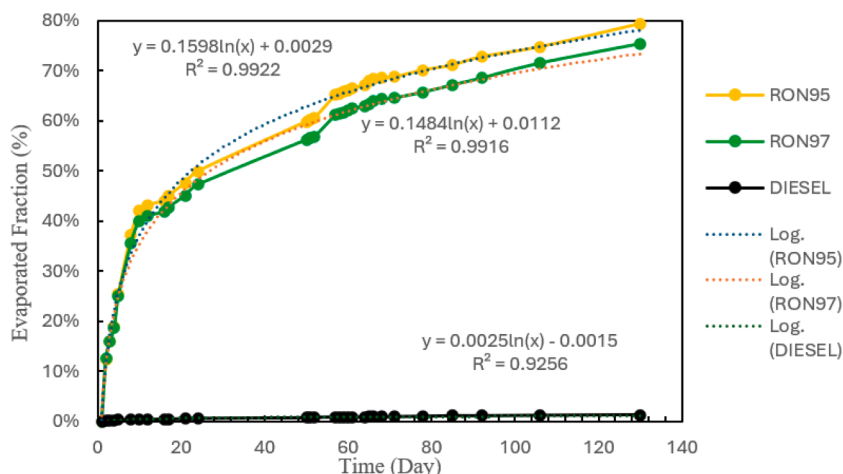


Fig. 3. Logarithmic curve fit of RON95, RON97, and Diesel vs. time.

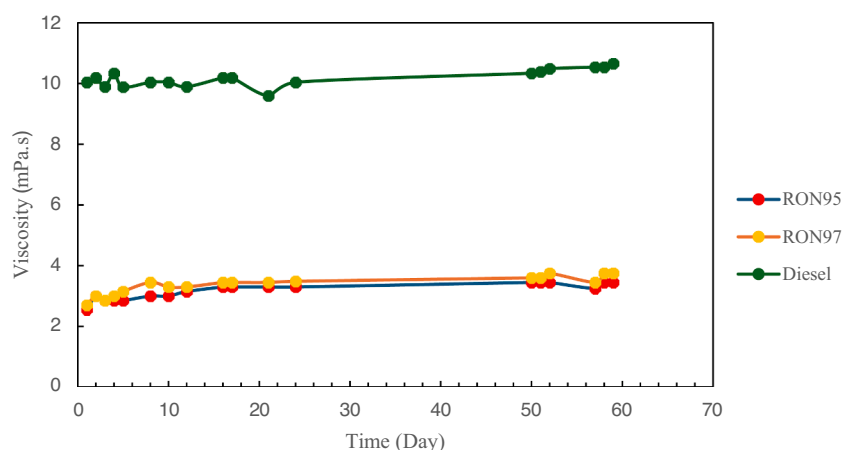


Fig. 4. Viscosity vs. time.

observed rheological shifts.

During the initial phase, it took only two days for both RON95 and RON97 to reach a viscosity of 2.998 mPa.s. Abrupt data fluctuations occurred between the 3rd and 12th days for the gasolines, and between the 2nd and 24th days for Diesel. These initial variations may have been influenced by day-to-day fluctuations in ambient laboratory temperature during testing, as temperature can affect the viscosity of hydrocarbon liquids. Following this, from the 12th to the 50th day, the viscosity rates of the gasolines steadily raised as the attraction between remaining heavier hydrocarbon molecules strengthened.

3.3. Chromatographic speciation of hydrocarbon shifts

GC-FID analysis was employed to examine changes in the hydrocarbon components during the weathering period. Table 2, together with the corresponding chromatograms shown in Figs. 5, 6, and 7, presents the changes in peak height and concentration of the three major components identified in each fuel.

For RON95 (Fig. 5), the primary peak at a retention time of 1.589 min decreased from an initial concentration of 21.18% (peak height: 28,563,751) to 18.16% (peak height: 116,641). Similarly, the second

Table 2
Summary of selected peak characteristics for different fuel types.

Component	Reference Fuel			Old Fuel		
	RON95	RON97	Diesel	RON95	RON97	Diesel
1st Peak						
Retention Time (min)	1.589	1.574	2.397	1.583	1.567	2.400
Height	28,563,751	11,010,040	1,050,077	116,641	18,280	713,432
Concentration (%)	21.18	17.94607	5.624849	18.16	0.006534	4.929
2nd Peak						
Retention Time (min)	1.649	1.758	4.284	1.672	1.762	4.301
Height	11,337,647	34,288,911	818,991	216,553	19,958,012	808,702
Concentration (%)	14.89238	20.84487	7.062843	3.362227	9.743627	6.403
3rd Peak						
Retention Time (min)	1.759	1.964	6.423	1.761	1.987	6.460
Height	22,701,059	17,494,505	523,226	13,907,391	42,520,684	519,997
Concentration (%)	18.89915	14.99523	7.930964	6.021078	33.42898	6.777

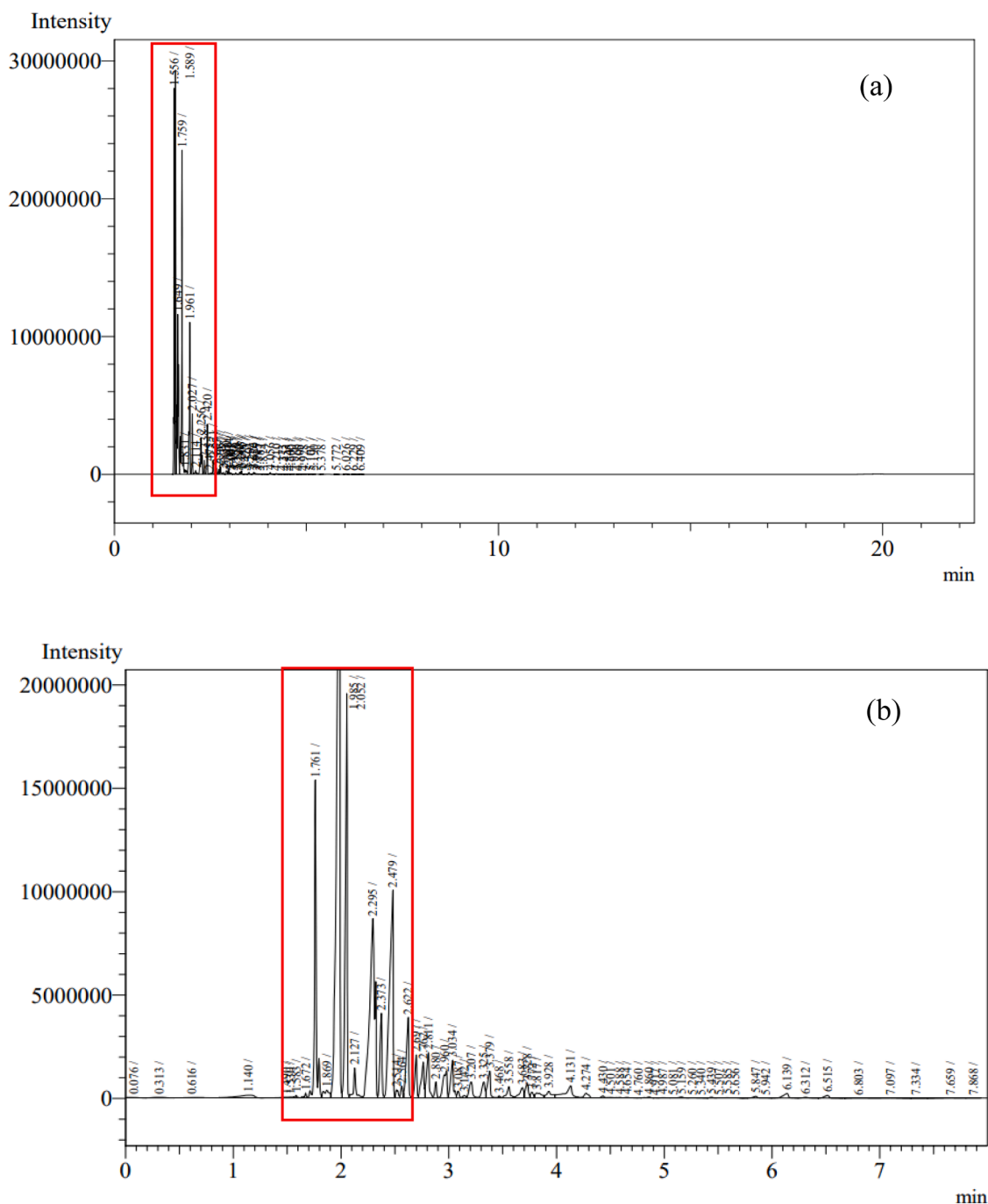


Fig. 5. Gas chromatography plots of (a) reference RON95 fuel and (b) old RON95 fuel.

peak at 1.649 min decreased from 14.89% to 3.36%, while the third peak at 1.759 min declined from 18.90% to 6.02%. These changes may suggest that some of the lighter hydrocarbon components were progressively lost to the surrounding atmosphere during the evaporation process.

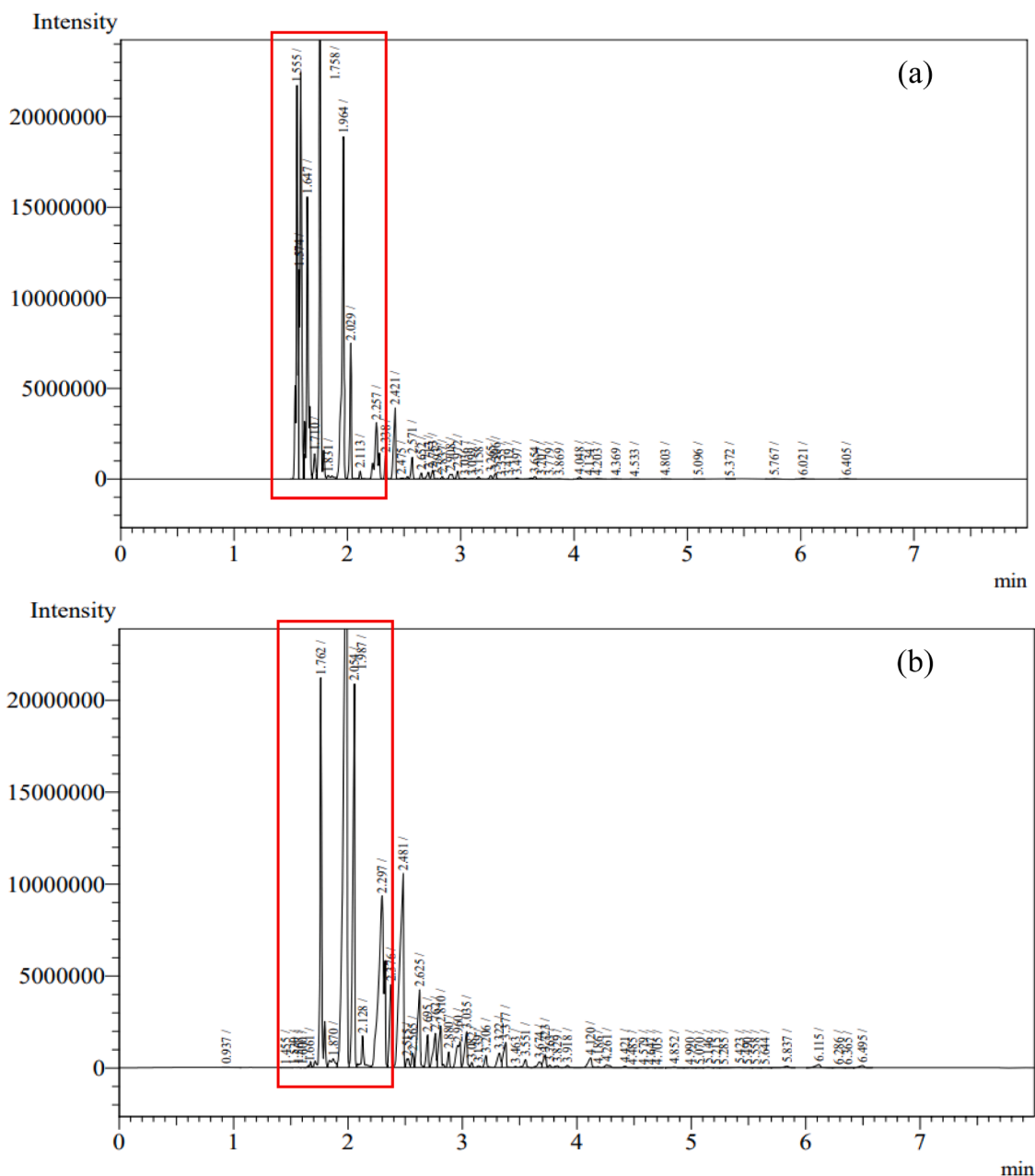
RON97 (Fig. 6) showed relatively substantial changes. The first peak, at a retention time of 1.574 min, decreased from 17.95% to 0.0065%, suggesting an almost complete reduction in its relative concentration. The second peak, at 1.758 min, also decreased from 20.84% to 9.74%. In contrast, the third peak, at 1.964 min, increased from 14.99% to 33.43%, with the corresponding peak height increasing from 17,494,505 to 42,520,684. The changes in relative concentration may reflect changes in the composition of the fuel during weathering.

Diesel (Fig. 7) exhibited comparatively greater compositional

stability throughout the weathering period, as indicated by the relatively small changes in the major chromatographic peaks. The first peak, at a retention time of 2.397 min, decreased slightly from 5.62% to 4.93%. Similarly, the peak with the highest initial concentration, at 4.284 min, showed a moderate reduction from 7.06% to 6.40%, while the third peak, at 6.423 min, decreased from 7.93% to 6.78%.

3.4. Degradation of gross calorific value

The calorific value (CV) of the fresh and prolonged-storage fuel samples was evaluated using bomb calorimetry. The temperature profiles obtained during the calorimetric measurements are presented in Figs. 8, 9, and 10. Overall, differences in the temperature response between the reference and aged samples suggest that prolonged storage



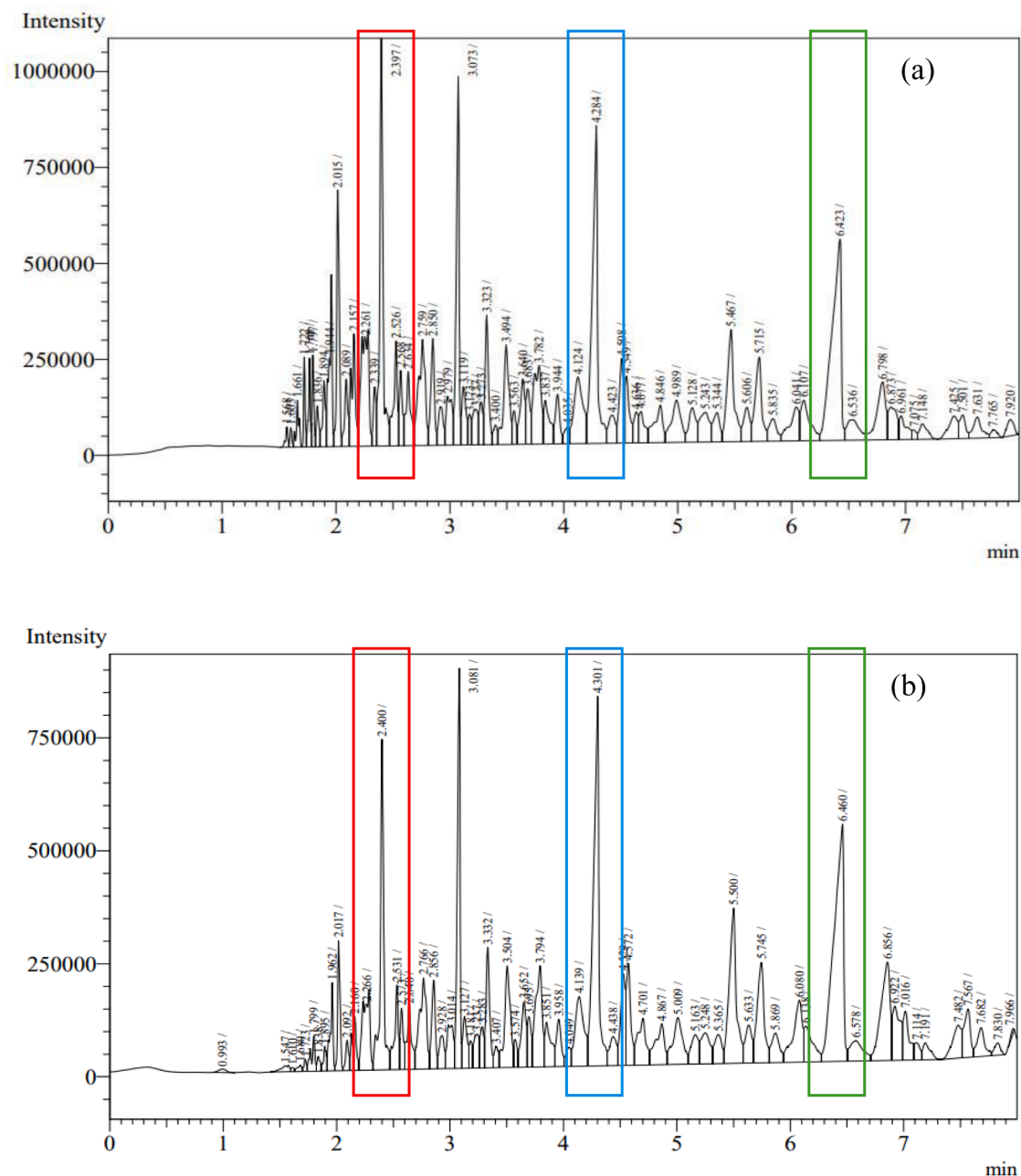


Fig. 7. Gas chromatography plots of (a) reference Diesel fuel and (b) old Diesel fuel.

functional groups, including C–O and O–O bonds, modifies the original hydrocarbon structure and reduces the energy released during complete combustion relative to the unoxidized fuel matrix. Thus, despite the concurrent concentration of heavier hydrocarbon fractions through evaporation, the net reductions in CV observed for RON95 (12.1%), RON97 (6.0%), and Diesel (4.9%) over 70 days suggest that oxidative degradation may have contributed to the observed decline in fuel energy content. Given that oxidative products were not characterized in the present study, this interpretation should be considered as a proposed mechanism rather than a definitive attribution.

4. Conclusions

In conclusion, prolonged open storage causes continuous evaporation of volatile light hydrocarbons and leads to significant changes in the properties of commercial vehicle fuels. Gasoline blends showed

substantial mass loss over 130 days, with RON95 and RON97 losing 79.32% and 75.00% of their initial mass, respectively, following a logarithmic evaporation pattern. In contrast, diesel showed much lower evaporation, with only 1.30% mass loss. As the lighter components evaporated, the viscosity of all fuels increased due to the greater proportion of heavier hydrocarbons remaining in the fuel. GC-FID analysis also showed a reduction in the lighter hydrocarbon components. Prolonged evaporation also reduced the gross calorific value of the fuels. After 70 days, RON95 showed the highest reduction of 12.1%, followed by RON97 at 6.0% and diesel at 4.9%. These findings show that prolonged open storage can change the physical, chemical and energy properties of commercial fuels, particularly gasoline.

While this study provides empirical insights into the weathering behavior of commercial fuels under tropical ambient conditions, several limitations should be acknowledged. First, although the observed reduction in calorific value may be associated with oxidative

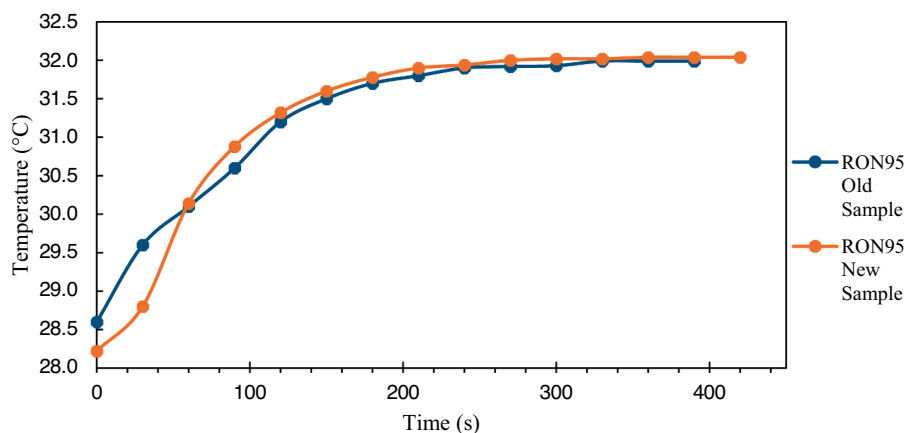


Fig. 8. Temperature activity between RON95 old sample and new sample.

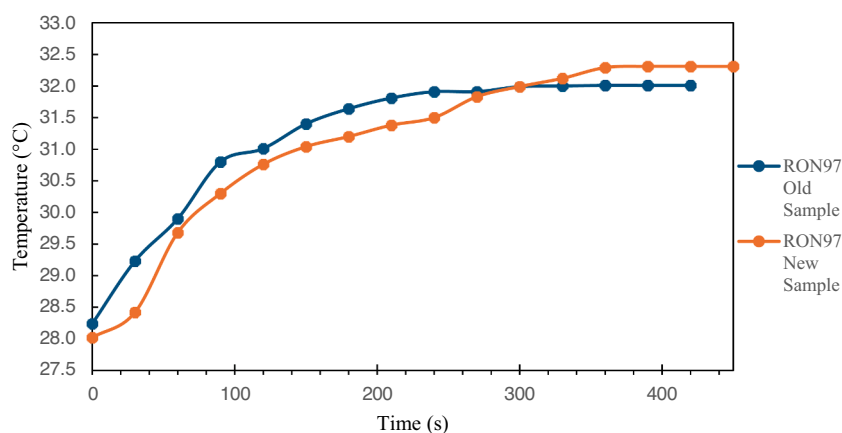


Fig. 9. Temperature activity between RON97 old sample and new sample.

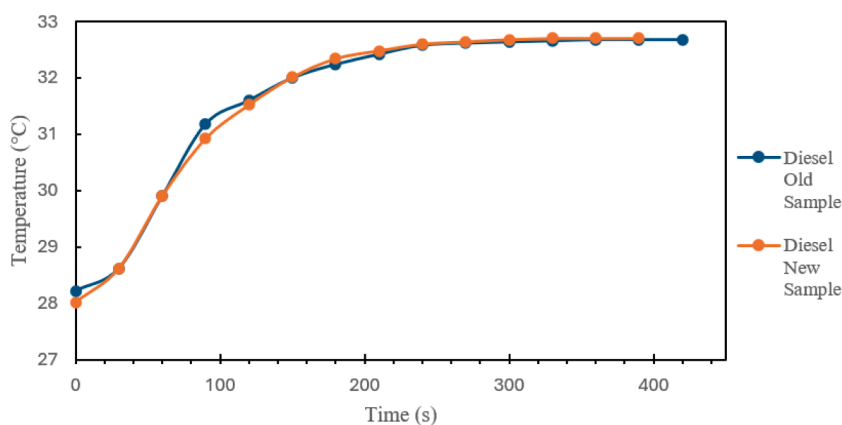


Fig. 10. Temperature activity between Diesel old sample and new sample.

degradation in addition to the evaporation of light fractions, the chemical oxidation products, such as hydroperoxides, carboxylic acids, and gums, were not directly identified or quantified. Therefore, the specific contribution of individual oxidation pathways could not be established. In addition, the findings are based on the specific commercial Malaysian formulations of RON95, RON97, and ULSD examined in this study. As fuel composition and additive packages may vary between regions and suppliers, the precise weathering and degradation rates observed here may not be directly applicable to other commercial fuel formulations.

To build upon the empirical baseline established in this study, future research may consider several areas for further investigation. First, more detailed chemical characterization using techniques such as GC-MS and FTIR could help identify and quantify oxygenated degradation compounds, including hydroperoxides and insoluble gum products, thereby providing further evidence regarding the possible contribution of oxidative processes to the observed reduction in fuel energy content. Second, the prolonged weathering behaviour of alternative fuel formulations, particularly bio-blended fuels such as B20/B30 biodiesel and E10 ethanol blends, could be examined under tropical atmospheric

Table 3

Summary of calorific value for fuels after 70 days of storage.

Type of Fuel	Calorific Value (cal/g)		Percentage of Reduction (%)
	Reference Fuel	Prolonged-storage Fuel	
RON95 unleaded gasoline	6333.81	5568.55	12.1%
RON97 unleaded gasoline	6648.44	6249.06	6.0%
Diesel	7759.78	7380.30	4.9%

conditions, as their responses to prolonged ambient exposure may differ from those of conventional petroleum-based fuels. Further work could also consider pilot-scale storage systems to examine how factors such as liquid surface area, thermal mass, and enclosed vapor headspace may influence evaporation behavior and long-term fuel stability under conditions more representative of practical storage environments.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used AI in order to assist with language editing, clarity improvement, and structuring of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Muhammad Aliff Ikhmal Zulkafli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Muhammad Abdullah:** Writing – review & editing, Validation, Resources. **Mohd Zahirasri Mohd Tohir:** Writing – review & editing, Validation. **Mohamad Syazarudin Md Said:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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