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Identification of Hydrocarbons Characteristics Using Low-Power Laser Absorption Spectroscopy

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Abstract

This study presents an experimental investigation into the detection of hydrocarbons using low-power laser absorption spectroscopy at 532 nm. Oil–water emulsions (0–4% v/v) were stabilized with a surfactant and analyzed in transmission. A hydrocarbon fingerprint was derived from the absorption band at 520–525 nm. The system demonstrated high sensitivity (<0.5%), rapid response, and strong linear correlation with concentration ($R^2 = 0.992$). The method achieved a limit of detection (LOD) of 0.29% and a limit of quantification (LOQ) of 0.97%. These results highlight the suitability of compact diode-laser systems for low-cost environmental monitoring and industrial safety.

Keywords: Hydrocarbon detection, absorption spectroscopy, tunable diode laser, hydrocarbon fingerprint, chemical pollution.

Introduction:

Transport activities, their persistence in aquatic ecosystems poses risks to human health, biodiversity, and water quality [1–3]. Conventional detection methods, including chromatography, mass spectrometry, and electrochemical sensors, provide high precision but require expensive instrumentation, skilled operators, and laboratory conditions [4,5]. In contrast, optical spectroscopic methods offer rapid, non-invasive, and field-deployable alternatives. Raman-based LiDAR and laser-induced fluorescence (LIF) techniques have been applied to detect oil films and measure thickness in situ [6,7]. Broadband cavity-enhanced absorption spectroscopy (CEAS) and tunable diode laser absorption spectroscopy (TDLAS) have achieved sub-ppm sensitivity for gas-phase hydrocarbons [8]. More recently, machine learning combined with LIF has improved robustness in classifying different oil types [9]. Despite these advances, there remains a research gap: reproducible methodologies for detecting hydrocarbons in liquid-phase emulsions using low-power, visible-band laser systems are limited. This study addresses this gap by employing a compact 532 nm diode laser to detect low-percentage oil–water emulsions and extract hydrocarbon fingerprints at 520–525 nm. This paper is organized as follows: Section 2 introduces the theoretical framework. Section 3 describes the experimental design and materials. Section 4 presents the results. Section 5 discusses sensitivity and applicability. Section 6 concludes.

Theoretical Framework

The absorption of hydrocarbons in aqueous media follows the Beer–Lambert law, expressed as

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$$A \equiv \ln\left\{\frac{I_0(\lambda)}{I(\lambda)}\right\} = \varepsilon cl \qquad \dots(1)$$

where A is the absorbance, $I_0(\lambda)$ and $I(\lambda)$ are the incident monochromatic intensity and the transmitted intensity after propagation, respectively, c is the concentration of the absorbing species, and l is the optical path length. The extinction coefficient εcl is a central spectroscopic parameter, often termed molar absorptivity. In scattering media such as emulsions, deviations from this ideal relationship are expected [6], requiring normalization and regression analysis for accurate quantification. When a sample is confined within a cell of length$l$l, bounded by planar, parallel, and non-absorbing walls at the wavelength of interest (Fig. 1), the Beer–Lambert law is applicable. Absorbance, as defined in (1), is automatically measured by modern photometric instrumentation.

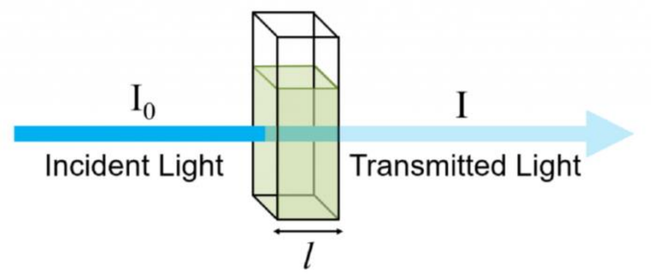

Figure (1): Light transmission through a sample solution

The absorbance is defined by Eq. (1) as the logarithmic ratio of the incident light intensity to the transmitted light intensity; it is automatically measured in modern optical instrumentation. The transmittance coefficient, T, may be provided by many photometric instruments [6], as

$$T \equiv \frac{I(\lambda)}{I_0(\lambda)} = \exp\{-\varepsilon cl\} \qquad \dots(2)$$

This expression shows the definition alongside the interpretation of optical processes according to the Lambert law, as seen in the Appendix.

In photometry analytical applications, it is not common to consider the effect of non-uniform absorber concentration, because such conditions rarely arise. However, the circumstances are different if the absorber is not photosensitive and undergoes decomposition or other conversion during the radiation experiment. Consequently, in such a case, the concentration will become heterogeneous, even though the solution is homogeneous at the beginning of the experiment [6].

Experimental Setup and Methods

Oil–water emulsions with motor oil concentrations of 0%, 1%, 2%, 3%, and 4% (v/v) were prepared in distilled water. To stabilize the emulsions, 1 mL of liquid soap was added as a surfactant, and the mixtures were homogenized using an electromagnetic stirrer. Reference measurements were taken for pure oil, water, and surfactant to isolate the contribution of hydrocarbons. The optical setup (Fig. 2) consisted of a low-power diode laser operating at 532 nm directed through a quartz cuvette of path length$l$l. The transmitted light intensity was collected using a silicon photodiode coupled to a data acquisition (DAQ) system. Calibration was performed prior to each run to ensure accuracy and reproducibility. The DAQ-recorded intensity values were processed using Python. Signal processing included baseline correction, Savitzky–Golay smoothing, and regression analysis to separate absorption from scattering effects. Hydrocarbon contributions were quantified by comparing transmitted intensities across different concentrations. The system demonstrated strong linearity between absorbance and hydrocarbon concentration, as shown in Table 2. The limit of detection (LOD) and limit of quantification (LOQ) were calculated as

$$LOD = \frac{10\sigma}{S}3S, \qquad LOQ = \frac{3\sigma}{S}S10\sigma \quad \ldots(3)$$

where σ is the standard deviation of baseline noise and S is the slope of the regression line. This unified experimental–analytical approach enabled accurate quantification of hydrocarbon concentrations in aqueous media.

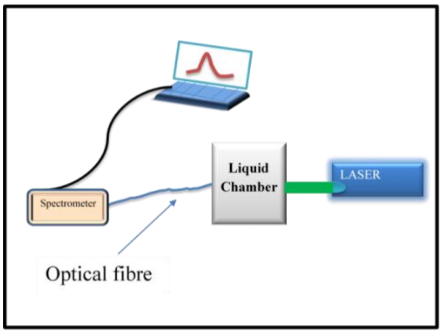

Fig. 2. Annotated experimental setup for hydrocarbon detection using low-power laser absorption spectroscopy.

Table 2. Calibration results for hydrocarbon detection.

Concentration (% v/v)	Peak Absorbance (a.u.)	Normalized Intensity (I/I_0)	Calculated Absorbance $A = -\ln(I/I_0)$	Replicates (n)	%RSD
0 (blank)	0.000	1.000	0.000	5	–
1	0.085	0.919	0.085	5	4.2
2	0.171	0.843	0.171	5	3.9
3	0.255	0.775	0.255	5	3.5
4	0.342	0.710	0.342	5	3.1

Table 2: Regression statistics for calibration curve (Absorbance vs. concentration).

Regression Model	Slope (S)	Intercept	R^2	RMSE	LOD ($3\sigma/S$)	LOQ ($10\sigma/S$)
Absorbance vs. %	0.085	0.002	0.992	0.012	0.29 %	0.97 %

Results and Discussion

The transmission spectra, as shown in Fig. 3, reveal concentration-dependent hydrocarbon features. A consistent absorption peak appeared near 520 nm across all samples, while an additional peak at 525 nm was observed in emulsions, absent in pure references. Normalization of spectra minimized variability due to focal spot fluctuations, laser stability, and heterogeneous scattering. The calibration curve showed excellent linearity (*R*2=0.992R2=0.992) and low residual errors (RMSE = 0.012). Sensitivity analysis confirmed the method's ability to detect concentrations below 0.5% v/v, with calculated LOD = 0.29% and LOQ = 0.97%. The %RSD across replicates was below 5%, indicating high reproducibility.

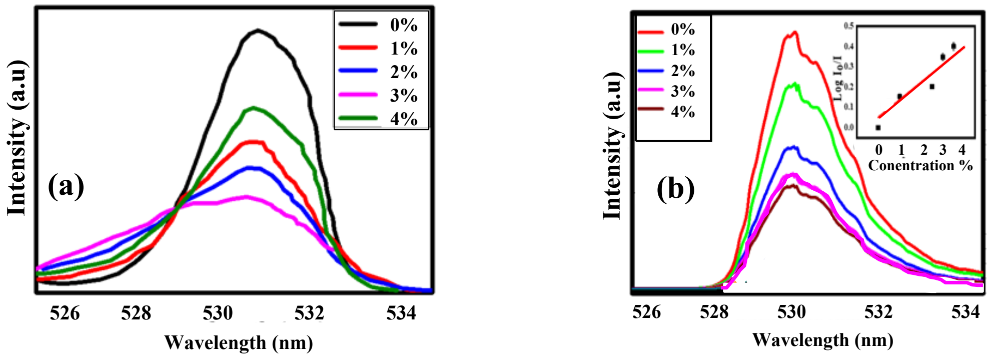

Figure (3): transmission spectrum (a) water and liquid soap (b) water and hydrocarbons at concentrations (0, 1, 2, 3, 4 %).

Conclusion

This study confirms that low-power diode-laser absorption spectroscopy is a reliable and cost-effective technique for hydrocarbon detection in aqueous emulsions. The method demonstrated high sensitivity, rapid response, and reproducibility, making it suitable for environmental monitoring and industrial safety applications. Future work will focus on miniaturizing the system for field deployment and extending the approach to a broader range of hydrocarbons and complex mixtures.

Appendix

Extended Mathematical Formulations of Beer–Lambert Law in its differential form is

$$\frac{dI}{dx} = -\varepsilon c l \qquad \ldots (A1)$$

where x is the dimension of the optical path along which traveling light, this is a more fundamental construction formula and not exactly anchored to any particular experiment or geometry.

Another mathematical formula of Lambert law is denoted by terms of cross-sectional area of the cell (S) and the amount of absorber, which is presented by the number of moles (n), is given by

$$A = \frac{\varepsilon n}{S} = \varepsilon l c_{average} \quad \ldots (A2)$$

The expression shows the validity of whether the concentration is uniform or not. This is expected since the number of light-absorbing molecules present is what matters, not their distribution.

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