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Betanin-Driven Multimodal Sensor Platform for Qualitative and Quantitative Detection of Petrol Adulteration

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Abstract

Fuel adulteration, particularly with kerosene, remains a significant concern affecting engine performance, air quality, and regulatory compliance. In this study, we report the development of a multi-technique analytical platform utilizing betanin, a naturally occurring pigment, for the detection of kerosene adulteration in petrol. A 0.1% betanin solution was prepared and applied to evaluate visual colorimetric changes in adulterated fuel samples at varying kerosene concentrations (5%, 10%, 20%). The detection system employed four analytical approaches: colorimetric analysis, UV-Visible spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, and thin-layer chromatography (TLC) on betanin-coated plates. Colorimetric changes were recorded over 24 hours, showing progressive fading correlated with kerosene content. Spectrophotometric analysis demonstrated a measurable decline in absorbance at 538 nm with increasing adulteration, while FTIR confirmed alterations in functional groups, particularly alcohol- and hydrocarbon-related peaks. TLC analysis revealed increasing spot size with higher kerosene levels, indicating effective chromatographic separation. This integrated method proves that betanin can serve as a sensitive, eco-friendly, and low-cost probe for fuel adulteration detection, suitable for both laboratory validation and potential field deployment.

Keywords: Petrol adulteration, Betanin, Colorimetric sensor, Kerosene detection, Natural dye probe

Abbreviations

FTIR: Fourier Transform Infrared
NIR: Near Infrared
TLC: Thin-Layer Chromatography
IPA: Isopropanol
UV: Ultra-Violet
PLS-DA: Partial Least Squares Discriminant Analysis
GVE: Gaseous Vapor Emission

1. Introduction

The adulteration of fuels, especially petrol, with cheaper substances like kerosine is a widespread issue affecting the economy and environmental safety. Lower costs and easy accessibility make kerosine a common adulterant in many developing countries.[2] Fuel adulteration is often carried out through diversion and manipulation of petroleum products, resulting in artificial scarcity and illegal exportation to neighbouring regions for increased profits at the cost of consumer trust and economic stability.[6] Such practices compromise engine performance as well as increase pollutant emissions, contributing to air quality degradation and health hazards, and long-term damage to internal combustion engines. Detecting this adulteration is crucial for maintaining fuel quality standards, and protecting consumers and the environment.

A wide range of methods have been developed to detect kerosene adulteration in petrol, ranging from traditional physicochemical analyses to advanced spectroscopic and sensor-based technologies. Preliminary insights can be obtained from conventional approaches like measuring density, viscosity, or octane number. However, they often lack the sensitivity required to detect low-level adulteration and are time-consuming.[3,9] Advanced techniques like Fourier transform infrared (FTIR) and near-infrared (NIR) spectroscopy, often combined with chemometric tools like Partial Least Squares Discriminant Analysis (PLS-DA), have improved speed and accuracy while minimizing sample preparation.[1] Similarly, sensor-based technologies such as dielectric constant sensors, load cell sensors, and Fiber Bragg Grating (FBG) sensors enable real-time, portable detection suited for on-road applications.[8] Emerging methods such as terahertz waveguide sensors, photonic crystal fiber-based sensors, and gaseous vapor emission (GVE) analysis show promise for field deployment, but still require extensive validation.[2,4,7] Kerosene adulteration in petrol presents a complex challenge with technical, regulatory, and socio-economic implications. Although advanced detection techniques like spectroscopy and sensor-based systems show promise, their widespread use is limited by high costs and limited accessibility. Addressing this issue requires stronger regulatory enforcement, greater public awareness, and the development of affordable, portable detection tools.

This study focuses on utilizing betanin, a beetroot extract, as a green-method to detect kerosine adulteration in petroleum, providing a simple, cost-effective, and time-saving approach. By analyzing both visual and instrumental indicators over time across varying concentrations of kerosene, we demonstrate a clear correlation between adulterant levels and betanin degradation, offering a potential tool for rapid field-level screening. Our approach combines colorimetric analysis, UV-Visible spectroscopy, FTIR spectroscopy, and thin-layer chromatography (TLC), forming a robust detection strategy. Observable color fading, reduced absorbance at 538 nm, characteristic FTIR spectral changes, and distinct TLC separation patterns collectively highlight betanin's effectiveness as a low-cost, sensitive detection agent. This approach bridges the gap between laboratory-grade techniques and practical on-site applications. The method has been formally recognized and documented in our granted patent.[5]

2. Experimental Design

2.1. Sample Preparation

For this experiment, a 2% stock solution of betanin in distilled water was prepared. The stock solution was then diluted to 0.1% working solution using distilled water and ethanol in a ratio of 7:3. The pH of the working solution was maintained at 5.5. Three adulterated petrol samples were prepared with increasing kerosine concentrations of 5%, 10%, and 20%. The total volume of all samples was maintained at 7 ml, with 5 ml of pure petrol, and the calculated amounts of kerosine and 0.1% betanin solution. A control sample was also prepared with 5 ml of pure petrol and 2 ml of 0.1% betanin solution.

2.2. Colorimetric Detection of Petrol Adulteration

The samples were mixed gently after preparation and left to rest. They were observed for any visual changes in color at time intervals of 5 minutes, 3 hours, and 24 hours from sample preparation. When the betanin solution interacts with adulterated petrol, distinct colorimetric changes occur, indicating the presence of impurities. This provides a simple visual cue for detection.

2.3. Absorption Spectra Analysis by ultra-violet (UV) Spectroscopy

For quantitative analysis, the absorbance of the control and adulterated samples was measured at 538 nm using a spectrophotometer. The absorbance graph is an essential tool for assessing the effectiveness of the betanin-based method in detecting petrol adulteration. It visually represents how the absorption spectrum of the betanin solution alters when combined with petrol and different concentrations of kerosene.

2.4. Fourier Transform Infrared (FTIR) Peak Analysis

FTIR spectroscopy is used to analyze the changes in the functional groups and molecular structure of the petrol when adulterants are present. Characteristic shifts in the FTIR peaks help identify the type of adulteration. The intensity mode was shown in % transmittance, resolution was 4 cm^{-1}, number of scans taken were 45, and the apodization function used was Happ-Genzel to improve the signal quality y controlling the distribution of energy across data points.

2.5. Detection of Petrol Adulteration through Paper-based Sensor

The paper-based sensor in this experiment relies on the principle of thin-layer chromatography (TLC). It is a separation technique used to isolate, identify, and analyze the components of a sample. It is a versatile and inexpensive technique that is fast, straightforward, and crucial for the rapid identification of components, hence making it a reliable fit for detection of petrol adulteration. A paper-based TLC sensor offers a rapid, cost-effective, and portable solution for detecting kerosine adulteration in petrol. It is a simple, highly sensitive technique that is capable of detecting adulteration even at low levels. 6 cm* 6 cm TLC silica plates were used with markings for spots placed 2 cm from each other. Before loading the pure control and kerosine-adulterated samples, the plate was coated with 0.1% betanin solution and air-dried. Spots for pure petrol, along with 5%, 10%, and 20% kerosine-adulterated samples, were applied using capillaries and air-dried. A 9:1 ratio of n-hexane and toluene was used as the solvent in which the TLC plate was placed for approximately 5 minutes allowing the solvent to migrate until 1 cm from the plate's edge. The plate was then visualized under short-wavelength UV light.

3. Results and discussion

3.1. Colorimetric Analysis

In the presence of only petrol, initially transparent with a faint yellowish hue, characteristic of pure petrol, is observed with no visible reaction or color change. In the presence of only betanin, depending on its concentration, a deep red to magenta is observed. This also shows its stability and strong coloration due to its pigment.

Immediately after mixing, petrol and 0.1% betanin mixture has a bright pink or reddish showing uniform dispersion of betanin in petrol. The same mixture after 3 hours fades into a pale pink. This is due to the degradation of betanin caused by interaction with petrol components. However, some pigmentation still remains and the reddish-pink hue is still distinguishable despite visible fading. After 24 hours, the mixture turns pale or completely colourless. The significant fading of the reddish-pink hue occurs because of the degradation of betanin.

After mixing petrol, 5% kerosine, and 0.1% betanin solution, the mixture is a slightly lighter shade of reddish-pink as compared to the mixture of petrol and 0.1% betanin solution. 3 hours later, the 5% kerosine mildly accelerates betanin degradation and causes the mixture to have a lighter shade of pink than the mixture of petrol and 0.1% betanin solution. The colour difference between 0% kerosine and 5% kerosine adulteration is slight, but noticeable. After 24 hours, the colour has a slightly lighter pinkish hue compared to its initial appearance, but has faded to nearly the same extent as the mixture of petrol and 0.1% betanin solution.

After mixing petrol, 10% kerosine, and 0.1% betanin solution, the mixture undergoes noticeable colour dilution, tending towards pale pink. After 3 hours, there is more significant degradation than in the 5% mixture due to the higher amount of kerosine affecting betanin stability. Consequently, the mixture shows a diluted pale pink colour, lighter than the 5% kerosine adulterated mixture. After a total of 24 hours, moderate fading can be seen, but some pink colouration may still persist. However, there is still a visible distinction between 5% and 10% kerosine adulteration.

Upon initial observation, the mixture with petrol, 20% kerosine, and 0.1% betanin solution, is a weak pink, indicating the reduced solubility or masking of betanin's colour by the increased kerosine concentration. After 3 hours, the high kerosine concentration strongly reduces betanin solubility leading to accelerated fading and a faint pink or nearly colourless solution. The reddish-pink color is almost completely washed out, indicating severe degradation or masking. After 24 hours, it is a nearly colourless, washed-out solution wherein the betanin was either degraded or masked due to high kerosene content.

These results demonstrate that increasing concentrations of kerosene in petrol accelerate the degradation of betanin, causing a progressive and measurable fading of its reddish-pink coloration over time. This visible trend enables a potential visual indicator-based method for detecting kerosene adulteration. These observations are clearly depicted in Figure 1, showing the gradual color change in mixtures across different kerosene concentrations and time intervals.

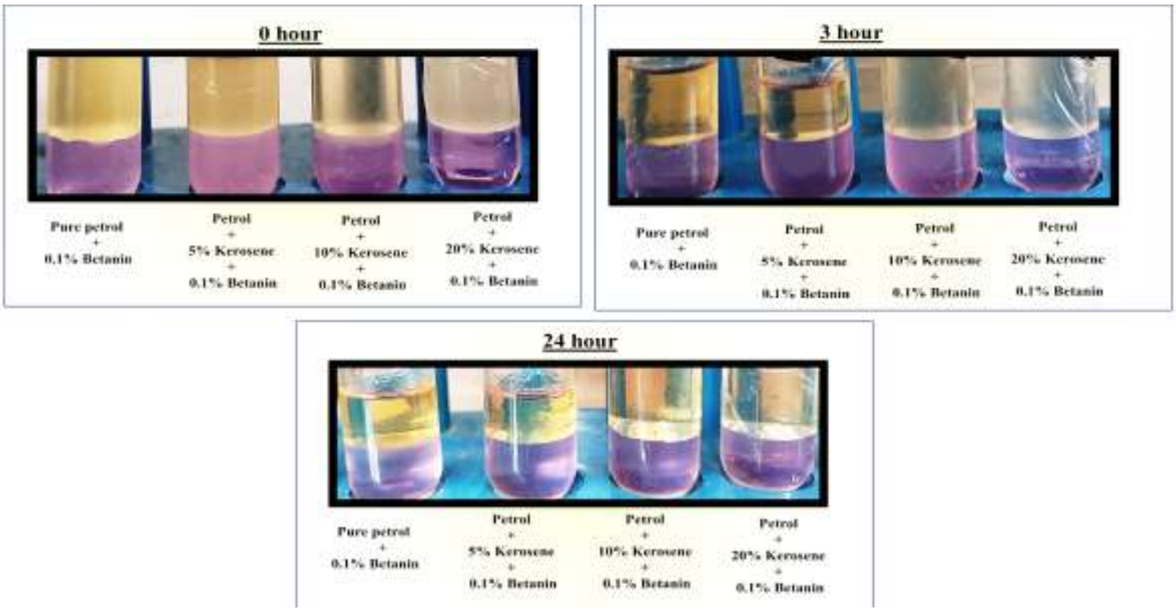

Figure 1. Colorimetric analysis of petrol adulterated with kerosene (5%, 10%, 20%) and 0.1% Betanin at 0, 3, and 24 hours.

3.2.Spectroscopic Analysis

Figure 2 represents the absorbance graph showing a strong absorbance peak of pure petrol mixed with 0.1% betanin, confirming the stability and presence of betanin in the absence of adulterants. As kerosene is added to the petrol-betanin mixture, a clear decrease in absorbance is observed. A reduction in the absorbance peak is noticed at 5% kerosine adulteration. This trend is applicable for 10% and 20% kerosine concentrations as well, indicating the role of kerosine in masking betanin's colour. The absorbance graph also reflects changes over time. After 3 and 24 hours, there is a continued decline in absorbance, reflecting the degradation of betanin. This degradation is synonymous with the visual observation of colour fading. The absorbance graph validates the presence of betanin and demonstrates how its stability diminishes in the presence of kerosene. The results indicate that increased kerosene concentrations lead to greater reductions in absorbance.

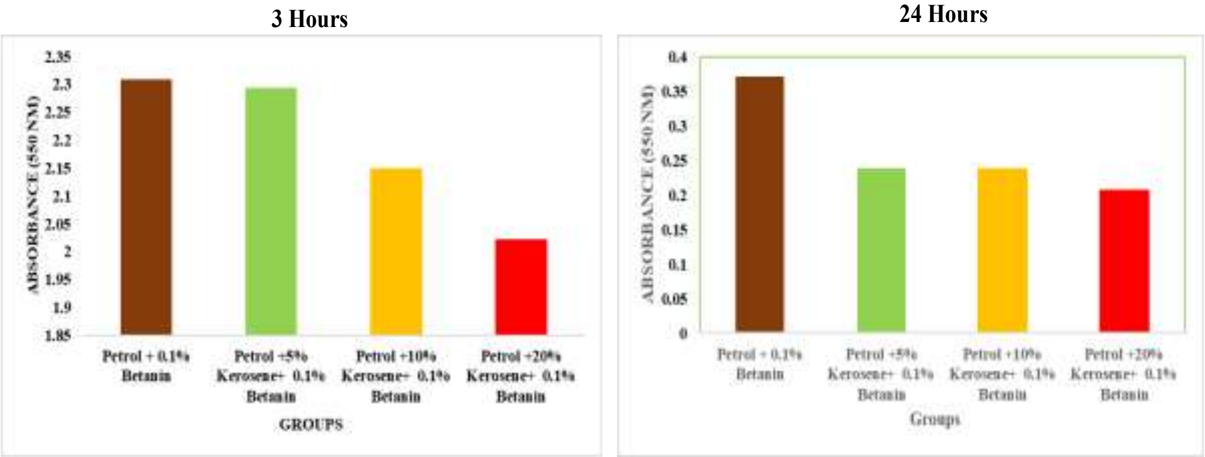

Figure 2. Absorption spectra graph of petrol adulterated with kerosene (5%, 10%, 20%) and 0.1% Betanin at 3 and 24 hours.

3.3.FTIR Analysis

Figure 3 illustrates a graphical representation of FTIR spectra of petrol with 0.1% Betanin (control). Peaks in specific wavenumber ranges can help identify functional groups. ~3300 cm^{-1} could indicate O-H stretching, possibly from the hydroxyl group, ~2900 cm^{-1} indicates C-H stretching from alkane groups, ~1400 1500 cm^{-1} shows likely due to C-H bending vibrations, and ~1000-1200 cm^{-1} suggest C-O stretching vibrations showing characteristic of alcohols. For the sample containing petrol, 5% kerosine, and 0.1% betanin solution, the spectrum provided shows peaks in the range of 500 cm^{-1} to 4500 cm^{-1}. The spectral data observed was consistent with the functional groups in isopropanol (IPA). For the sample containing petrol, 10% kerosine, and 0.1% betanin solution, the spectrum provided shows peaks in the range of 500 cm^{-1} to 4500 cm^{-1}. The peaks confirm the presence of functional groups corresponding to IPA: hydroxyl (-OH) and alkyl (-CH) groups. No significant peaks outside the expected range for IPA are observed. For the sample containing petrol, 20% kerosine, and 0.1% betanin solution, the spectrum provided shows peaks in the range of 500 cm^{-1} to 4500 cm^{-1}, as typical for FTIR. The peaks confirm the presence of functional groups corresponding to IPA, such as hydroxyl (-OH) and alkyl (-CH) groups. The variety of functional groups points to a complex structure, possibly indicative of an alcohol or an ether with associated hydrocarbons.

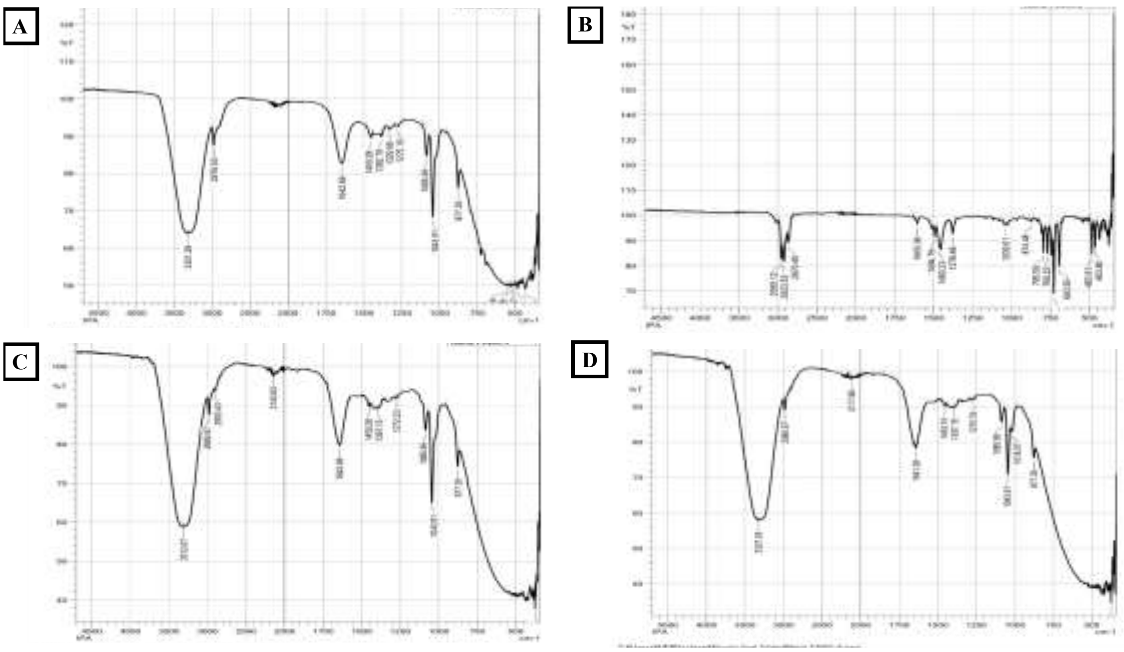

Figure 3. FTIR spectra of petrol with 0.1% Betanin (control) and petrol adulterated with kerosene at 5%, 10%, and 20% concentrations. Key absorption peaks indicate functional groups associated with petrol and kerosene, with variations reflecting the increasing presence of kerosene.

3.4. TLC Analysis

The TLC plate was placed in the n-hexane – toluene solvent for 5 minutes and was then visualized using short-wavelength UV light. Upon visualization, it was found that the spots had sufficiently migrated with the solvent and a noticeable difference in the size of each spot could be observed. As indicated by the measured dimensions in Figure 4, spot size increased with an increase in kerosine concentration. The figure depicts the differences in spot sizes, with the highest level of adulteration, i.e. 20%, having the largest spot size in both length and width. The pure petrol sample displays the smallest spot size, while the kerosine-adulterated samples display progressively larger sizes with an increase in the concentration of kerosine from 5% to 20%, indicating a clear correlation between the level of adulteration and spot size.

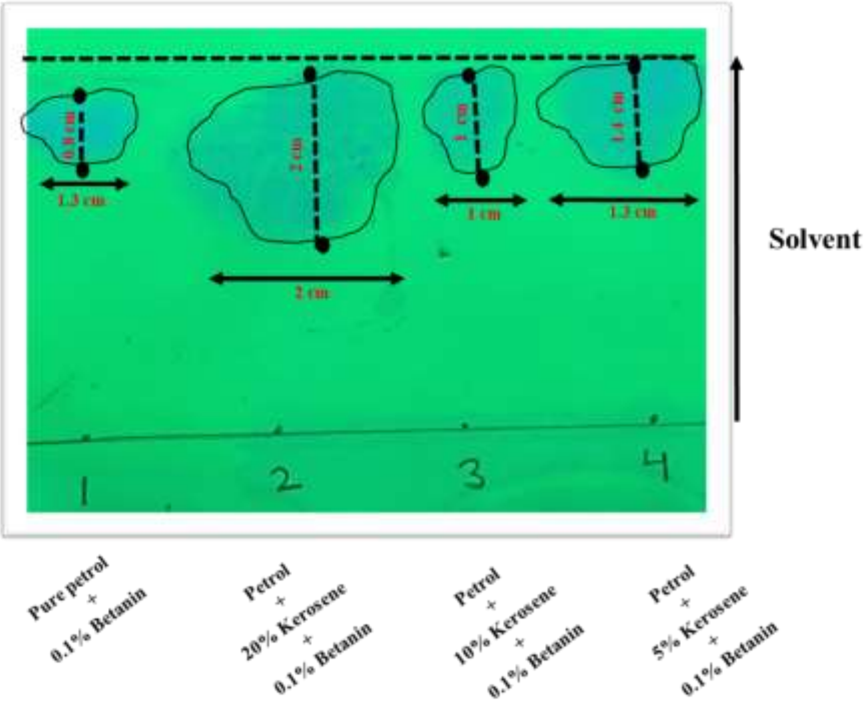

Figure 4. TLC analysis of pure petrol (spot 1), and kerosene-adulterated petrol samples with 20% (spot 2), 10% (spot 3), and 5% (spot 4) adulteration. Spot sizes increase with kerosene concentration, as indicated by the measured dimensions.

The results demonstrate that the TLC method, combined with a 0.1% Betanin coating, is effective for detecting and differentiating levels of kerosene adulteration in petrol. The proportional increase in spot size with increasing adulteration provides a simple and visual way to assess the extent of contamination.

Conclusion:

The present study successfully demonstrates the utility of betanin, a natural pigment, as a sensitive and visual indicator for the detection of kerosene adulteration in petrol. The simple colorimetric reaction between betanin and adulterated fuel presents an immediate visual cue, which is further supported by quantitative absorption spectroscopy, functional group analysis via FTIR, and the separation capability of TLC. The study observes a progressive degradation of betanin as kerosene concentrations increase, confirming its reactivity and sensitivity to hydrocarbon composition changes.

The results suggest that betanin's color change is not only visually detectable but also measurable through absorbance spectroscopy, which shows a consistent decrease in peak intensity with rising kerosene content. FTIR spectral analysis confirms chemical alterations in functional groups caused by kerosene, while the TLC-based detection system successfully differentiates levels of adulteration based on the spread and intensity of chromatographic spots.

The combined use of visual, spectroscopic, and chromatographic techniques enhances detection confidence, ensuring the method's reproducibility and robustness. This study highlights a cost-effective, rapid, and reliable method for detecting kerosene adulteration in petrol using a natural colorant—betanin. The combination of colorimetric detection, UV-visible spectroscopy, FTIR, and TLC allows for a comprehensive assessment. Betanin acts as an effective probe for real-time field diagnostics, exhibiting visible color transitions and quantifiable spectral changes in response to adulterants. With increasing environmental and regulatory demands for cleaner fuels, this approach offers a sustainable and accessible solution for adulteration monitoring.

Future Directions

To enhance the applicability and efficiency of the proposed detection method, future research should focus on miniaturizing the system into portable, field-ready paper-based kits that can be used by non-specialists. Integrating smartphone-based colorimetric analysis applications would allow real-time, quantitative interpretation of color changes, reducing human error and enabling instant documentation. The scope can also be extended by validating the method across various commercial fuel blends and under different storage or environmental conditions to ensure robustness. Furthermore, expanding the sensor's capability to detect a broader range of adulterants such as diesel or naphtha, and integrating the system with IoT-based supply chain monitoring for continuous fuel quality tracking, would significantly improve its real-world utility and adoption in regulatory frameworks.

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