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Oil Sense: An Automated Optical Analysis System for Real-Time Cooking Oil Quality Assessment

Raj Dinesh Yadav[1], Shivang Mukesh Mandvia[2]

[1]Student, Vidya Varidhi Vidyalaya & Junior College, Maharashtra, India.
[2]Assistant Manager, Learning Links Foundation, New Delhi, India.

Abstract - *The repeated reuse of cooking oil is a prevalent practice in households, restaurants, and street food stalls globally. However, excessive reheating triggers complex chemical degradation, specifically oxidation and polymerization, leading to the formation of harmful compounds such as aldehydes and free radicals. These substances pose severe health risks, including cardiovascular diseases, systemic inflammation, and carcinogenicity. Furthermore, the Food Safety and Standards Authority of India (FSSAI) stipulate a 25% threshold for Total Polar Compounds (TPC), beyond which oil is unfit for consumption. Current quality assessment methods rely on subjective sensory inspection, which is inherently unreliable. This research presents Oil Sense, a low-cost, portable Arduino-based diagnostic tool designed to scientifically evaluate cooking oil quality. The system integrates an Arduino Mega 2560 with a TCS34725 RGB color sensor (utilizing a 4x gain and 50ms integration time) and a Light Dependent Resistor (LDR) to measure spectral shifts and turbidity. By calculating a Green-to-Red (GR) ratio and light attenuation metrics, the device classifies oil into 'Unused', 'Reusable', or 'Cannot be Used' (Unfit) categories. Real-time data and status alerts are provided via a 16x4 I2C LCD, tri-color indicator of LEDs, and a buzzer. This device offers a high-fidelity, affordable solution for improving food safety standards in domestic and commercial kitchens.*

Key Words: **Cooking Oil Reuse, Food Safety, Oil Quality Detection, Arduino Mega 2560, TCS34725 Colour Sensor, Turbidity Detection, Optical Sensing**

1. INTRODUCTION

1.1 Contextual Background

Cooking oil serves as a primary heat-transfer medium in culinary processes. In commercial environments, such as street food stalls and high-volume restaurants, oil is frequently subjected to multiple frying cycles to reduce operational overheads. While economically advantageous, the repeated thermal exposure significantly alters the oil's molecular structure, compromising both nutritional value and consumer safety.

1.2 Health Risk Analysis

The thermal degradation of edible oils is characterised by oxidation, polymerisation, and the breakdown of fatty acids. These reactions facilitate the formation of toxic secondary metabolites, most notably aldehydes and free radicals. Chronic consumption of these lipid oxidation products is clinically linked to hypertension, cardiovascular heart disease, and digestive disorders [2]. A critical metric in assessing these risks is the concentration of Total Polar Compounds (TPC). The Food Safety and Standards Authority of India (FSSAI) has established a regulatory limit of 25% TPC [1]; oil exceeding this threshold is considered toxic and unfit for human consumption.

1.3 Problem Statement

Current methods for evaluating oil quality in domestic and small-scale commercial settings are predominantly sensory based, relying on visual darkening or the detection of rancid odours. Such methods are highly subjective and often fail to detect harmful chemical changes that occur prior to significant physical alteration. While laboratory-grade chromatography and TPC meters provide high precision, their prohibitive cost and time-intensive nature render them inaccessible for daily monitoring.

1.4 Proposed Solution

'Oil Sense' is proposed as a scientific, low-cost, and portable alternative for real-time oil assessment. By employing a dual-sensor optical approach, the device provides an objective analysis of oxidative state and particulate contamination, enabling users to maintain compliance with safety standards like those set by the FSSAI.

2. MATERIALS AND SYSTEM ARCHITECTURE

2.1 Component Breakdown

The 'Oil Sense' hardware architecture is designed for precision and reliability:

- Arduino Mega 2560: The primary microcontroller, selected for its multiple serial ports and extensive I/O capacity.
- TCS34725 RGB Colour Sensor: A high-sensitivity sensor configured with a 4x Gain and 50ms Integration Time to detect minute spectral shifts.

- LDR (Light Dependent Resistor) Module: Utilised to quantify light attenuation and turbidity.
- 16x4 I2C LCD: Provides a comprehensive user interface for displaying RGB values, ratios, and quality status.
- Tri-colour Indicator LEDs (Green, Yellow, Red): Provide immediate visual feedback on oil safety.
- Buzzer: Issues audible alerts when oil is classified as 'Unfit'.
- White LED Source: A stabilised 5V light source for optical path consistency.
- Transparent Test Tube: The sampling vessel ensuring a fixed path length for light transmission.

2.2 System Design

The system employs a transmissive optical design. A controlled beam from the white LED passes through the oil sample held in the test tube. The TCS34725 and LDR sensors are positioned diametrically opposite the light source. This arrangement allows the system to measure how the oil's chemical degradation affects light absorption (spectral shift) and scattering (turbidity).

To ensure the accuracy, repeatability, and reliability of the optical readings, the 'Oil Sense' testing environment is strictly controlled. First, to eliminate interference from ambient room lighting, the test tube receptacle is housed within a completely opaque, custom-designed enclosure. During testing, the sample is isolated, ensuring that the TCS34725 and LDR sensors exclusively measure the light emitted by the system's controlled internal LED. Furthermore, to mitigate fluctuations in optical clarity, refractive index, and viscosity caused by heat, a standardized thermal protocol is enforced. All oil samples are allowed to cool to standard ambient room temperature prior to analysis. This ensures that transient thermal states do not skew the optical transmission, allowing for a consistent comparative baseline across all tests.

2.3 Circuitry

The device leverages the I2C communication protocol for high-speed data transfer between the microcontroller and the colour sensor.

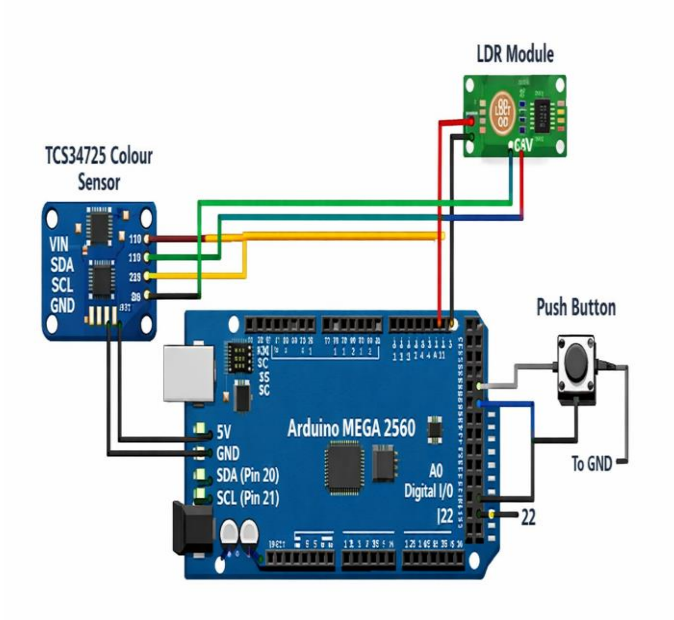

Fig -1: Circuit Diagram showing the Arduino Mega 2560, TCS34725 Color Sensor (SDA/SCL), LDR Module (A0), and Push Button connections.

The TCS34725 is connected to the Arduino Mega via Pin 20 (SDA) and Pin 21 (SCL). The LDR module is interfaced through Analogue Input A0, while a push button on Digital Pin 22 triggers the diagnostic sequence.

3. WORKING PRINCIPLE AND SENSOR LOGIC

3.1 Technical Logic (The GR Ratio)

The core diagnosticlogicrelies on the normalisation of raw spectral data to eliminate errors caused by light attenuation and ambient fluctuations.

- **Normalisation:** The red channel is normalised using the clear channel (c) value:
  red = (r * 255) / c.
- **GR Ratio Calculation:**
  grRatio = (float)green / red.

The accumulation of Total Polar Compounds (TPC) is the standard chemical marker for oil degradation. As TPC levels rise toward the 25% FSSAI threshold [1], the oil undergoes significant physical changes, most notably a darkening in color driven by the formation of conjugated dienes and polymeric compounds. Optically, these complex lipid degradation products heavily absorb shorter wavelengths of light (green/blue) while transmitting longer, red wavelengths. Therefore, the intensity of green light passing through the oil decreases proportionally to the red light. By calculating the Green-to-Red (GR) ratio, the device effectively uses this spectral absorption profile as a direct, inverse optical proxy for TPC concentration. A lower GR ratio serves as a primary indicator of higher oxidative degradation.

3.2 Classification Thresholds

The system processes two primary metrics: the spectral GR ratio for chemical darkening and the LDR value for turbidity (where a higher analogRead value indicates higher light resistance/particle concentration). *According to the Beer-Lambert law, the presence of suspended particulate matter (turbidity) scatters and absorbs the transmitted light. As particulate concentration increases, light attenuation occurs, reducing the photon density reaching the LDR surface. Because the LDR's electrical resistance is inversely proportional to light intensity, higher turbidity results in greater electrical resistance, triggering the 'Unfit' status.*

For this proof-of-concept prototype, the classification thresholds for both the GR Ratio and LDR values were established empirically through systematic observational analysis. Samples of cooking oil at various stages of thermal degradation were tested in the device. By correlating the physical and sensory degradation of these samples with the corresponding sensor outputs, baseline heuristic thresholds were defined. While these observational baselines successfully demonstrate the system's capability to differentiate oil quality, future iterations of this research will involve calibrating these optical values against laboratory-grade TPC meters.

Table -1: Sensor Based Classification Thresholds (Validated for Groundnut and Sunflower Oils)

Sensor Metric	Value/Threshold	Resultant Classification
GR Ratio	< 0.12	Unused Oil
GR Ratio	1.0 – 3.5	Reusable Oil
GR Ratio	0.12 – 1.0 or > 3.5	Cannot be Used
LDR Value	> 700	Unfit (High Turbidity)
LDR Value	400 – 700	Medium Quality
LDR Value	< 400	Good Quality

3.3 Software Flow

Upon activation, the program initializes the I2C bus and verifies the sensor state. When the user presses the test button, the white LED is pulsed. The Arduino captures the RGB and LDR data, calculates the GR ratio, and compares these values against the stored logic thresholds. The final classification is then simultaneously pushed to the 16x4 LCD, the corresponding indicator LED, and the buzzer for Unfit samples.

4. RESULTS AND ANALYSIS

4.1 Prototype Performance

Testing of the 'Oil Sense' prototype demonstrated high sensitivity to oil darkening. For this baseline study, empirical testing and threshold calibrations were conducted using refined groundnut oil and subsequently validated against refined sunflower oil. Because both of these common cooking mediums share a similar pale-yellow baseline spectral profile, they exhibited identical degradation thresholds (e.g., crossing the 'Unfit' threshold at a GR Ratio < 0.12). It is important to note, however, that oils with inherently darker or greener baseline spectral profiles (such as raw mustard or virgin olive oil) possess different initial chromosphere concentrations. Therefore, while the fundamental logic of spectral shift applies universally, these specific numerical thresholds are currently validated specifically for light-profile oils. The 16x4 LCD successfully rendered real-time R, G, B, and GR values, alongside a clear textual status. During trials with used commercial oil, a GR ratio of 0.40 correctly triggered the 'Cannot be Used' status, reflecting the non-linear degradation path of complex lipid chains.

Fig-2: Physical Prototype of Oil Sense in action, showing the LCD displaying R, G, B, and GR values with the 'Used Oil' status.

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Table -2: Comparative Analysis The performance of the 'Oil Sense' device was benchmarked against traditional assessment methods:

Feature	Manual Inspection	Lab Testing	Oil Sense Device
Accuracy	Low (Subjective)	Very High	Moderate-High (Objective)
Cost	Negligible	High (per test)	Low (one-time)
Ease of Use	Very Easy	Requires Specialists	Very Easy
Result Time	Instant	24–72 Hours	< 2 Seconds

5. FUTURE SCOPE & ENHANCEMENTS

5.1 AI and Machine Learning

While the current optical thresholds are successfully calibrated for light-profile mediums like groundnut and sunflower oil, the static system cannot natively adjust to drastically different baseline colors, such as dark mustard oil. Future development will focus on integrating machine learning models for dynamic calibration. By training the system on diverse optical datasets encompassing various base mediums, the device will be able to autonomously identify the oil type and apply oil-specific TPC estimations with much higher precision across all oil variants.

5.2 IoT Connectivity

Integration of a Wi-Fi or Bluetooth module (e.g., ESP32) will enable mobile application syncing. This allows commercial kitchen managers to log oil quality trends and receive automated alerts when oil batches reach the FSSAI 25% TPC limit.

5.3 Thermal Cycle Tracking

The addition of a non-contact infrared temperature sensor would allow the device to monitor the number of heating cycles and the duration of high-temperature exposure, providing a more holistic view of oxidative stress.

6. CONCLUSIONS

The 'Oil Sense' device provides a robust, evidence-based solution to a significant public health challenge. By combining spectral analysis and turbidity measurement into a low-cost, portable platform, it bridges the gap between unreliable sensory methods and expensive laboratory diagnostics. Implementing this technology in households and street-side eateries can significantly reduce the consumption of toxic lipid oxidation products, thereby improving long-term food safety and public health outcomes.

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BIOGRAPHIES

	Student Name: Raj Dinesh Yadav Grade:10th School Name: Vidya Varidhi Vidyalaya
	Mentor Name: Shivang Mukesh Mandvia Company Name: Learning Links Foundation