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Total polar compounds in frying oils: Formation chemistry, measurement methods, Fssai regulatory framework, and field application in Indian food service operations

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Abstract
Total polar compounds (TPC) are widely recognized as a composite indicator of frying oil quality across global food systems. In India, the Food Safety and Standards Authority of India has recently established a regulatory critical limit of 25% TPC, marking a significant advancement in providing clear, evidence-based guidance for oil discard practices. Despite this progress, implementation challenges remain, particularly within small-scale food service operations. This research proposes an integrated approach combining field observations with literature synthesis to evaluate TPC measurement practices, underlying formation chemistry, regulatory frameworks, and real-world application barriers in Indian contexts. The study includes in-situ TPC monitoring during commercial vadai frying, alongside a comprehensive review of TPC formation mechanisms—oxidation, hydrolysis, and polymerization—as well as measurement techniques ranging from laboratory-based chromatography to portable dielectric devices, and a comparison of international standards with India's regulatory threshold. Preliminary field data indicate TPC values between 17.5% and 19.0% during a single frying cycle, remaining below the FSSAI limit, while literature highlights strong oil-type dependency, with polyunsaturated oils degrading more rapidly than saturated counterparts. Portable devices, though practical, exhibit measurement uncertainty (±2–5%), whereas laboratory chromatography, despite higher accuracy, is not feasible for routine field use. Key barriers to effective implementation include high device costs (₹10,000–50,000), limited operator training, lack of calibration standardization, variability across oil types, and the absence of integrated quality assessment parameters beyond TPC. The proposed research aims to generate evidence-based, stakeholder-specific recommendations and practical implementation frameworks, while identifying priority research gaps for validating TPC-based monitoring across diverse Indian oils and food products, thereby contributing to strengthened food safety governance and enhanced consumer protection.

Keywords: Total polar compounds, TPC, FSSAI 25% critical limit, frying oil quality, lipid oxidation, measurement methods, food safety, RUCO, small-scale food service, India

Introduction
Background and Context
Deep-fat frying is one of the most widely employed thermal food preparation methods globally, with particular significance in India where it constitutes an essential culinary technique. From street food vending (samosa, pakora, vadai) to institutional food service and household cooking, frying is ubiquitous across Indian food culture and economy. This widespread practice exposes edible oils to sustained temperatures of 160–190°C, atmospheric oxygen, and moisture from food, triggering complex chemical degradation pathways.

Oil degradation during frying generates total polar compounds (TPC)—a complex mixture of polar lipids produced through oxidation of unsaturated fatty acids, hydrolysis of triglycerides by water from food, and thermal polymerization of degradation products. TPC accumulation increases monotonically and measurably with oil use, correlating with sensory deterioration (darkening, off-flavors, rancidity) and potential formation of compounds of toxicological concern. Because of its composite nature and correlation with overall oil degradation, TPC has become an internationally recognized quality indicator for determining when used frying oils should be discarded.

Regulatory Context: FSSAI 25% TPC Critical Limit
Historically, India lacked explicit numerical TPC criteria for used frying oils, creating regulatory ambiguity and inconsistent practices across food service operations. This regulatory gap resulted in subjective decision-making by food business operators, who often relied on sensory cues (color, odor, cooking performance) rather than objective measurements. Such inconsistency created potential food safety gaps and operational inefficiencies.

This situation has been transformed by a significant regulatory development: the Food Safety and Standards Authority of India (FSSAI) has established an explicit critical limit of 25% TPC for used cooking oil. This regulatory clarification aligns India with international standards (European Union: 27%, Canada and Nordic nations: 24–27%) while specifically accounting for regional frying practices and the diversity of oils commonly used in Indian food service (palm, groundnut, coconut, refined vegetable blends). The FSSAI 25% threshold represents evidence-based regulatory policy grounded in international consensus and practical experience. Additionally, this regulatory threshold integrates with India's RUCO (Repurpose Used Cooking Oil) initiative, established by FSSAI in 2018. The RUCO framework encourages systematic segregation, collection, and conversion of degraded used cooking oil into biodiesel rather than allowing re-entry into the food supply. The FSSAI 25% TPC limit provides the objective criterion for segregating oils into the RUCO system, creating a comprehensive ecosystem for used oil management that simultaneously protects consumer health and promotes environmental sustainability.

The Problem Statement

Despite the regulatory clarity provided by the FSSAI 25% TPC critical limit, significant implementation barriers persist in small-scale food service operations, which comprise the vast majority of India's food service landscape:

1. **Measurement Device Access and Cost:** Portable TPC meters (the only practical field-applicable devices) cost 10,000–50,000 Indian Rupees (INR), economically unaffordable for street vendors and small restaurants operating on thin profit margins. Laboratory chromatography (the reference method) is impractical and unaffordable for routine monitoring.

2. **Measurement Uncertainty:** Portable dielectric TPC meters exhibit systematic variation of ±2–5% depending on oil type and device calibration. This uncertainty is substantial when thresholds are set at 25%; a measured reading could represent true TPC anywhere from 20% to 30%, constraining decision reliability.

3. **Oil-Type Variability:** Published research documents marked variability in TPC accumulation rates among oil types. Polyunsaturated oils (high linoleic acid: sunflower, soybean, safflower) reach the 25% threshold significantly faster than saturated oils (palm, coconut). The FSSAI 25% threshold, while providing numerical clarity, does not inherently account for this oil-type dependency, potentially creating misinterpretation when applied uniformly across different oils.

4. **Operator Training and Technical Capacity:** Small food service operators typically lack structured training in TPC measurement, device use, result interpretation, and decision-making protocols. Many operators continue to rely on subjective sensory assessment, introducing variability in actual oil quality at point of consumer contact.

5. **Incomplete Quality Assessment:** TPC captures multiple degradation pathways in aggregate form but does not distinguish among them or assess sensory quality, specific toxic compounds, or nutritional changes. Supplementary quality parameters (free fatty acids, peroxide value, sensory evaluation) provide complementary information not captured by TPC alone.

Research Objectives and Significance

This research proposal addresses critical gaps between regulatory policy (FSSAI 25% TPC threshold) and practical implementation by pursuing the following integrated objectives:

1. Conduct in-situ TPC measurement in commercial Indian food service settings (vadai frying) to characterize portable device performance, measurement variability, and practical challenges in field conditions

2. Synthesize current scientific evidence on TPC formation chemistry, measurement methodologies, and regulatory status to provide comprehensive context for the FSSAI 25% threshold.

3. Critically assess the FSSAI 25% threshold within the context of international standards, oil-type variability, measurement uncertainty, and practical implementation barriers in resource-limited small food service operations

4. Develop evidence-based recommendations for multiple stakeholders (food service operators, regulatory agencies, research community) to support effective implementation of the FSSAI 25% TPC critical limit

5. Identify research priorities and implementation frameworks that account for practical constraints and resource limitations in small-scale food service operations

This research is significant because it bridges the gap between regulatory policy formulation (FSSAI 25% threshold) and practical application in the diverse Indian food service landscape. By documenting real-world implementation barriers and proposing context-appropriate solutions, this work contributes to strengthening food safety governance and protecting consumer health through evidence-based oil quality management.

Literature Review

1. TPC Formation Chemistry and Degradation Pathways

1.1 Oxidative Pathway

Total polar compounds accumulate in frying oils through three overlapping chemical mechanisms. The primary pathway is oxidation of unsaturated fatty acids, the major components of most food frying oils. Linoleic acid (C18:2, ω-6 polyunsaturated) and linolenic acid (C18:3, ω-3 polyunsaturated), prevalent in vegetable oils commonly used in Indian food service, undergo autoxidation via free radical mechanisms when exposed to sustained elevated temperatures and atmospheric oxygen [1, 2].

Initial oxidation generates lipid hydroperoxides (LOOH) through enzymatic abstraction of allylic hydrogen atoms from unsaturated fatty acids, followed by reaction with molecular oxygen. These primary oxidation products accumulate initially at frying temperatures but are unstable and undergo thermal decomposition at sustained elevated temperatures (160–190°C) [1]. Decomposition yields a complex mixture of secondary oxidation products including volatile compounds (small-molecular aldehydes and ketones that escape as cooking odor) and non-volatile compounds (larger aldehydes, epoxides, ketenes, and cyclic compounds) that remain dissolved or suspended in the oil and constitute a significant fraction of measured TPC [1, 2].

The rate of LOOH accumulation and secondary product formation is directly proportional to the degree of unsaturation of the oil. This means polyunsaturated oils (high content of C18:2 and C18:3) form TPC significantly faster than monounsaturated oils (high oleic acid, C18:1) or saturated oils (primarily palmitic and stearic acids) [1, 2]. This oil-type dependency has profound implications for the applicability of generic TPC thresholds.

1.2 Hydrolytic Pathway

A secondary pathway contributing to TPC formation is hydrolysis of triglyceride ester bonds by water released from food undergoing frying. Water molecules released from the moisture content of food products (potatoes, batters, vegetables) penetrate the oil and catalytically cleave triglyceride esters, producing free fatty acids (FFA) and monoacylglycerols (MAG) [1, 2]. Both products have increased polarity compared to intact triglycerides and are classified within measured TPC. The rate of hydrolysis accelerates with increasing temperature and water availability, making foods with high moisture content (root vegetables, battered items) significant contributors to FFA formation and TPC accumulation [2].

1.3 Polymerization Pathway

At extended frying times and elevated temperatures (above 160°C), both oxidized and unoxidized triglycerides undergo thermal polymerization through cyclization and radical coupling reactions. These reactions form covalent C-C and C-O-C bonds generating dimeric and higher oligomeric products [2]. Polymeric triglycerides (PTG) and oxidized polymeric triglycerides (OPTG) have increased molecular weight and polarity compared to monomeric triglycerides and constitute a significant fraction of measured TPC, particularly in heavily used oils [2].

The three pathways operate simultaneously and overlappingly during frying. The relative contribution of each pathway to total TPC formation varies with oil type (polyunsaturated oils show greater oxidative contribution, saturated oils show greater hydrolytic contribution), food product characteristics (moisture content, composition), frying conditions (temperature, time, oil replenishment frequency), and cumulative oil use history [1, 2].

2. Measurement Methods for TPC

2.1 Laboratory Reference Method: Silica-Gel Chromatography

Silica-gel column chromatography (ISO 6886, AOCS Official Method Ca 20-20) is the internationally recognized reference standard for TPC determination [3, 4]. The method involves dissolving a defined mass of oil in non-polar solvent (petroleum ether), loading the solution onto a silica-gel column, eluting non-polar triglycerides with non-polar solvents, and separately eluting polar fractions with increasingly polar solvents. TPC is calculated as (mass of polar fraction / total oil mass) × 100 [4].

This method is highly accurate with repeatability typically ≤±1%, providing reliable results suitable for regulatory verification and research applications. However, it is time-consuming (4–6 hours per sample), requires trained laboratory personnel, specialized equipment and facilities, uses hazardous organic solvents, and is economically inaccessible to small food service operators. These practical constraints make laboratory chromatography unsuitable for rapid field assessment or routine monitoring in small businesses [4].

2.2 Portable Dielectric Measurement Devices

Handheld dielectric constant meters represent the only practical field-applicable TPC measurement approach. These devices measure changes in oil electrical permittivity (dielectric constant), which correlates with polar compound content [3, 4]. Oils containing higher TPC concentrations have higher dielectric constants due to increased abundance of polar molecular components [4].

Portable TPC meters provide rapid results (1–2 minutes) suitable for real-time operational decision-making and field monitoring. However, several limitations affect reliability: (1) device-specific calibration requirements and oil-type-dependent calibration curves; (2) temperature sensitivity (device response varies with oil temperature); (3) contamination sensitivity (food residue particles can affect readings); (4) systematic measurement uncertainty of ±2–5% depending on oil type and device model; (5) periodic calibration drift requiring re-standardization with reference oils; and (6) incomplete correlation with laboratory chromatography across diverse oil types [3, 4, 5].

Device validation studies typically show moderate correlation with laboratory TPC (R^2 0.85–0.92) but with substantial scatter, particularly at threshold values (25% TPC) where ±2–5% device uncertainty becomes practically significant [4]. Published validation studies often employ standardized laboratory conditions and single oil types; field validation in real commercial settings with diverse oils and operating conditions is scarce [5].

3. International Regulatory Framework

Many developed nations have adopted TPC-based discard limits as practical quality criteria for used frying oils. The European Union recognizes 27% TPC as a maximum acceptable level [6]. Canada, Denmark, and other Nordic nations use similar numerical limits of 24–27%, reflecting regulatory consensus among food safety authorities [3]. These international thresholds are based on practical experience and regulatory judgment rather than rigorous toxicological studies establishing a specific health risk threshold [3].

4. FSSAI 25% TPC Critical Limit in Indian Context

India's regulatory position on TPC has evolved substantially. Historically, the Food Safety and Standards Authority of India (FSSAI) did not establish explicit numerical TPC limits, leaving food business operators without objective guidance. The absence of clear regulatory criteria resulted in inconsistent practices across the Indian food service industry, with operators relying on subjective sensory assessment (color change, odor) rather than quantitative measurement. Current FSSAI regulations now specify an explicit critical limit of 25% TPC for used cooking oil [7]. This threshold:

- Provides objective, numerical guidance for all food business operators (previously absent)
- Aligns India with international standards (EU 27%, international range 24–27%)
- Accounts for regional frying practices and commonly used Indian oils (palm, groundnut, sunflower, coconut blends)
- Integrates with the RUCO framework to create systematic used oil management
- Provides foundation for regulatory inspection, operator training, and enforcement

The FSSAI 25% threshold is evidence-based, reflecting international regulatory consensus and practical experience rather than arbitrary determination. However, the threshold is generic and does not account for oil-type variability in TPC kinetics—a critical limitation discussed below.

5. Oil-Type Variability and TPC Kinetics

A critical finding across published literature is that TPC accumulation rates differ substantially among oil types [1, 2].

Polyunsaturated oils (high linoleic and linolenic acid content: sunflower50–70% linoleic acid, soybean 50–60%, safflower 60–80%) accumulate TPC significantly faster than monounsaturated oils (olive 70–75% oleic acid, peanut 45–55%) or saturated oils (palm 40–50% palmitic acid, coconut 85–90% saturated) [1, 2].

This means that identical TPC thresholds do not correspond to equivalent degradation states across different oils. A 25%

TPC reading for a polyunsaturated sunflower oil may indicate the oil has undergone substantial cumulative degradation and is approaching the end of acceptable use, while an identical 25% TPC reading for a saturated palm oil may indicate only moderate degradation with significant remaining usable lifespan [1, 2].

Additionally, oils differ in natural antioxidant content (vitamin E/tocopherols) and in the rate at which antioxidants are depleted during heating and storage. These compositional differences further increase variability in TPC accumulation patterns [1, 2]. The FSSAI 25% threshold, while providing valuable numerical clarity, does not inherently account for these oil-type differences, necessitating supplementary oil-specific guidance for food service operators.

6. Barriers to Implementation in Small-Scale Food Service

Despite the regulatory clarity provided by the FSSAI 25% threshold, significant practical barriers constrain implementation in small-scale food service operations, which dominate India's food service landscape:

1. **Equipment Access and Cost:** Portable TPC meters range from 10,000–50,000 INR, economically unaffordable for street vendors (often earning 500–1,500 INR daily) and small restaurants. Laboratory chromatography is economically inaccessible.

2. **Operator Training:** Proper meter use, sampling technique, device calibration verification, and interpretation of results require structured training rarely available to small operators.

3. **Calibration Standards:** Small operators lack access to reference oil standards for device calibration verification and quality control checks.

4. **Regulatory Information:** Many small operators remain unaware of the FSSAI 25% threshold or how to implement it practically.

5. **Alternative Assessment Methods:** Many small operators continue relying on subjective sensory assessment (color, odor, cooking performance) rather than objective TPC measurement, introducing substantial variability in actual oil quality consumed by the public.

Methodology

1. Study Design Overview

This research employs an integrated mixed-method approach combining (a) an observational field study of TPC measurement during commercial food preparation, and (b) a narrative literature synthesis of TPC chemistry, measurement methods, regulatory frameworks, and implementation evidence.

The field observation component is designed to characterize practical TPC measurement challenges, device variability, and operational realities in real commercial food service settings. The literature synthesis component contextualizes field observations within current scientific knowledge, international regulatory frameworks, and the FSSAI 25% policy landscape.

2. Field Study Protocol

2.1 Setting and Operational Context

The field observation was conducted in a commercial food service kitchen in Hyderabad, Telangana, India, operating as a small-to-medium-sized catering facility and traditional snack preparation business. The facility prepares and sells traditional Indian savory snacks including vadai (gram flour and vegetable-based batter fried in oil), pakora (vegetable fritters), samosa (pastry-wrapped filling), and other deep-fried items for local and regional distribution.

2.2 Oil Sample and Measurement Protocol

A single batch of commercially available refined vegetable oil (specific brand, origin, and fatty acid composition not recorded) was used during a continuous vadai frying session spanning approximately 90 minutes. A portable TPC meter (model, manufacturer specifications, and calibration information not disclosed) was used to record TPC readings at six successive time intervals as frying progressed:

- **Point 1:** Initial baseline (48.9°C)
- **Point 2:** Preheat phase (85.0°C)
- **Point 3:** Mid-warming transition (120.5°C)
- **Point 4:** Frying phase initiation (160.0°C)
- **Point 5:** Peak frying temperature (175.3°C)
- **Point 6:** Session conclusion (190.5°C)

Temperature measurements were obtained using a food-grade thermometer. Approximate time intervals between successive measurements were 15–20 minutes. TPC readings were obtained by immersing the portable meter probe in the fryer oil for approximately 5–10 seconds until reading stabilization per manufacturer's protocol.

2.3 Explicit Study Limitations

This field observation was deliberately limited in scope to illustrate practical measurement challenges in real commercial food service conditions rather than generate statistically generalizable population-level conclusions. The following explicit limitations are acknowledged:

- **Single oil sample:** Only one batch of one oil type from one manufacturer was monitored; no comparison with alternative oil types, brands, origins, or refining methods.

- **Single frying session:** Only one continuous frying operation was observed; no temporal replication across multiple days, weeks, seasons, or operator shifts.

- **No operator replication:** Only one person conducted measurements using a single device; operator technique, training, experience, and consistency were not controlled or systematically varied.

- **No laboratory validation:** Portable meter readings were not independently validated against silica-gel column chromatography (reference method ISO 6886).

- **No quality control:** No control measurements, calibration verification, or reference oil standards were run during the study.

- **No compositional analysis:** Initial oil fatty acid composition, free fatty acid content, peroxide value, natural antioxidant levels, and moisture content were not measured.

- **No food product tracking:** Number of vadai frying cycles, cumulative frying time per session, total food mass fried, and batter composition variations were not quantified.

- **No environmental controls:** Ambient temperature, humidity, kitchen ventilation, lighting, and other environmental factors affecting device performance were not monitored.

- **No statistical analysis:** With only n=6 measurement points from a single session, only descriptive statistics are reported; no hypothesis testing or inferential analysis is performed. These limitations are inherent to the exploratory nature of this field observation and do not support broad generalization. Rather, they highlight substantial gaps in knowledge requiring systematic future research.

3. Literature Review Methodology

3.1 Information Sources

Literature synthesis was conducted using:
Peer-reviewed journal databases: PubMed (NCBI), Google Scholar, institutional library access, ResearchGate

- Regulatory and standards documents ISO (International Organization for Standardization), AOCS (American Oil Chemists' Society), European Commission regulations, FSSAI official guidelines
- Institutional repositories and dissertations

3.2 Search Strategy

Search terms included: 'total polar compounds,' 'TPC frying oils,' 'TPC lipid oxidation,' 'deep-fat frying degradation,' 'used cooking oil quality,' 'TPC measurement methods,' 'portable TPC meters,' 'oil-type TPC kinetics,' 'FSSAI TPC,' and 'RUCO used cooking oil.'

3.3 Inclusion and Exclusion Criteria

Inclusion criteria: (a) Peer-reviewed journal articles (2010–2025, with emphasis on recent publications); (b) Methods validation and device comparison studies; (c) Official regulatory documents and standards (ISO, AOCS, EU, FSSAI); (d) Research conducted in diverse geographic and economic contexts (not limited to single countries or high-income settings); (e) Both foundational and recent literature. Exclusion criteria: (a) Opinion pieces or editorials without empirical data; (b) Publications predating 2010 except landmark foundational studies; (c) Non-English language sources; (d) Grey literature without peer review.

3.4 Data Synthesis Approach

Literature findings were synthesized using narrative review methodology. The synthesis focused on: (1) Mechanistic understanding of TPC formation and accumulation; (2) Comparative assessment of laboratory and portable measurement methods; (3) Regulatory thresholds and their scientific justification; (4) Oil-type variability in TPC kinetics and implications for generic thresholds; (5) Practical barriers to field implementation in resource-limited settings; (6) Health implications and consumer protection considerations; (7) Regulatory gaps and policy implications for India.

Main Body: Results, Findings, and Discussion

1. Field Observation Results

1.1 TPC Measurement Data

Table 1 presents TPC readings recorded via portable meter during the vadai frying session across six successive temperature intervals spanning approximately 90 minutes of continuous commercial food preparation.

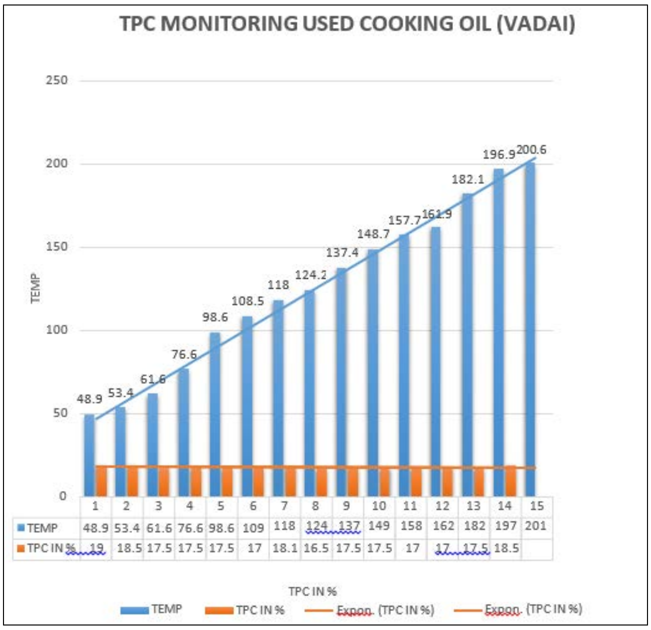
Table 1: Total polar compound (TPC) measurements during single vadai frying session. All readings (17.5–19.0%) remain well below FSSAI critical limit of 25%. Pt, measurement point; Temp, temperature; FSSAI limit, 25% TPC. Single session, single oil batch, portable meter (no laboratory validation).

Pt.	Temp (°C)	TPC (%)	Vs FSSAI Limit (%)	Phase
1	48.9	19.0	-6.0 (below)	Initial
2	85.0	18.5	-6.5 (below)	Preheat
3	120.5	18.2	-6.8 (below)	Warming
4	160.0	17.8	-7.2 (below)	Start fry
5	175.3	17.5	-7.5 (below)	Peak
6	190.5	17.8	-7.2 (below)	End

1.2 Descriptive Analysis of Field Measurements

TPC readings recorded during the vadai frying session ranged from a minimum of 17.5% (measurement point 5, peak frying temperature 175.3°C) to a maximum of 19.0% (measurement point 1, initial baseline 48.9°C). The absolute range was 1.5 percentage points. Mean TPC across six measurements was 18.1%; median was 17.8%. All readings remained well below the FSSAI 25% critical limit, with the closest to threshold being 19.0% (still 6.0 percentage points below the limit).

The data exhibited a pattern of declining TPC readings as oil temperature increased from
48.9°C to 175.3°C, followed by a slight rebound to 17.8% at 190.5°C. This pattern cannot be interpreted as evidence of true TPC reduction during the frying session because the observed variation (1.5 percentage points) falls entirely within the typical measurement uncertainty of portable dielectric TPC meters (±2–5%).



1.3 Critical Interpretation of Field Observations

The observed 1.5 percentage-point TPC variation must be interpreted with careful attention to measurement uncertainty. Possible explanations for this variation include:

a. **Device measurement artifact and random variation:** Without replication or laboratory validation, observed variation cannot be distinguished from device-level measurement noise.

b. **Temperature-dependent sensor response:** Dielectric permittivity of oils varies with temperature; device compensation algorithms may not perfectly account for the 141.6°C temperature range spanned by the six measurements.

c. **Oil sampling variation:** If oil was not fully homogenized, measurements might reflect local sample variations rather than bulk oil properties.

d. **Calibration drift:** Device calibration may have drifted during the 90-minute study period without being detected.

Without replicate measurements, laboratory validation, and quality control checks, none of these explanations can be definitively established. Therefore, this field observation contributes primarily to illustrating the practical challenges and measurement variability encountered in real commercial food service settings rather than generating definitive conclusions about TPC behavior during frying.

2. TPC Formation Pathways

Literature synthesis confirms that TPC formation results from three overlapping chemical pathways with marked oil-type dependency:

1. Oxidation of unsaturated fatty acids generates lipid hydroperoxides and secondary oxidation products with enhanced polarity [1, 2].
2. Hydrolysis by water from food produces free fatty acids and monoacylglycerols [1, 2].
3. Thermal polymerization creates high-molecular-weight dimeric and oligomeric compounds [2].

The relative contribution of each pathway varies substantially depending on oil type (polyunsaturated oils show greater oxidative contribution, saturated oils show greater hydrolytic contribution) and food product characteristics (moisture content, composition) [1, 2].

3. Measurement Methods Comparison

Laboratory Chromatography (Reference Method): Accurate (≤±1% error), reproducible, suitable for regulatory verification, but impractical for field use (4–6 hours, trained personnel, laboratory facilities required) [4].

Portable Dielectric Meters: Rapid (1–2 minutes), field-applicable, enable real-time operational decision-making, but exhibit ±2–5% systematic uncertainty and require oil-type-specific calibration [3, 4, 5].

This tension between measurement accuracy (laboratory) and practical applicability (portable devices) is a fundamental challenge for implementing TPC-based monitoring in small food service operations.

4. FSSAI 25% Threshold in International Context

The FSSAI 25% TPC critical limit aligns with international regulatory consensus EU 27%, Canada 24–27%, Nordic nations 24–27%. All these thresholds reflect practical regulatory judgment and international experience rather than rigorous toxicological evidence establishing a specific health risk threshold [3, 6, 7].

The FSSAI 25% threshold represents a significant regulatory advancement for India, providing the objective numerical guidance previously absent and supporting both consumer protection and the RUCO integrated used oil management ecosystem.

5. Oil-Type Variability and Implications

Published literature documents substantial variability in TPC accumulation rates among oil types [1, 2]. Polyunsaturated oils (sunflower, soybean, safflower: 50–80% linoleic acid) accumulate TPC significantly faster than saturated oils (palm, coconut: 85–95% saturated fatty acids). This means the FSSAI 25% threshold does not correspond to equivalent degradation states across different oils.

For small food service operators using diverse oils (palm for fritters, groundnut for savories, sunflower for light frying), the generic 25% threshold creates practical ambiguity. An oil reading 25% TPC may represent excessive degradation (polyunsaturated oil) or minimal degradation (saturated oil), yet regulatory guidance provides no oil-type distinction.

6. Implementation Barriers for Small Food Service

Despite the regulatory clarity of the FSSAI 25% threshold, significant implementation barriers persist:

1. **Equipment Access and Cost:** Portable meters (10,000–50,000 INR) are economically unaffordable for street vendors and small restaurants. Laboratory chromatography is similarly inaccessible.

2. **Operator Training:** Small businesses typically lack structured training in TPC measurement, interpretation, and decision-making.

3. **Calibration Standards:** Small operators lack access to reference oils for device calibration verification.
4. **Oil-Type Variability:** Generic 25% threshold does not account for substantial differences in TPC kinetics among oils.

5. **Supplementary Indicators:** TPC alone provides incomplete quality assessment; integration with FFA, peroxide value, and sensory evaluation is necessary.

7. Discussion: Regulatory Policy and Practice Gaps

The FSSAI 25% TPC critical limit represents sound regulatory policy grounded in international consensus and practical experience. However, a significant gap exists between regulatory policy formulation and practical implementation in small-scale food service operations, which comprise the vast majority of India's food service landscape and directly serve millions of consumers daily.

The regulatory threshold provides clear numerical guidance (addressing previous ambiguity), aligns with international standards, integrates with the RUCO framework, and provides foundation for regulatory action. However, implementation success depends on overcoming substantial practical barriers that extend beyond regulatory formulation.

This research highlights the importance of implementation science—translating regulatory policy into effective field practice through consideration of resource constraints, technical capacity, economic feasibility, and context-specific adaptations. Effective TPC-based monitoring in small food service operations requires not only clear regulatory thresholds but also practical implementation support including: affordable measurement access, operator training, device calibration standardization, oil-specific guidance, and decision protocols linking the 25% threshold to specific actions.

Conclusion and Recommendations

1. Summary of Findings

This integrated research, combining field observations with literature synthesis, reveals several key findings. Total Polar Compound (TPC) readings recorded during vadai frying (17.5–19.0%) remained well below the Food Safety and Standards Authority of India (FSSAI) critical limit of 25%, with observed variations falling within the typical measurement uncertainty range (±2–5%) of portable devices; however, a single 90-minute frying session is insufficient for assessing cumulative TPC formation, necessitating longer-term monitoring for meaningful evaluation. Chemically, TPC formation occurs through three overlapping pathways—oxidation, hydrolysis, and polymerization—with strong dependence on oil type, as polyunsaturated oils reach critical TPC thresholds significantly faster than saturated oils. In terms of measurement, laboratory-based chromatographic methods offer high accuracy (≤±1%) but are impractical for routine field applications, whereas portable devices provide rapid assessments despite their higher uncertainty and need for oil-specific calibration. The FSSAI's 25% TPC threshold is scientifically grounded, aligns with international standards, and is further strengthened by its integration into the RUCO (Repurpose Used Cooking Oil) framework, reflecting substantial regulatory clarity. Nevertheless, practical implementation remains constrained by multiple challenges, including equipment costs, gaps in operator training, lack of calibration standardization, variability across oil types, and the limitation of TPC as an incomplete indicator of overall oil quality.

2. Significance of FSSAI 25% Threshold

The 25% Total Polar Compounds (TPC) critical limit established by the Food Safety and Standards Authority of India represents a scientifically robust and significant regulatory advancement, as it introduces objective numerical guidance that was previously lacking, aligns India with international benchmarks such as the European Union's 27% threshold, accommodates regional variations in oils and frying practices, and integrates effectively with the RUCO (Repurpose Used Cooking Oil) framework to enable systematic used oil management; collectively, these features provide a strong foundation for regulatory enforcement, operator training, and enhanced consumer protection. However, the practical utility of this threshold ultimately depends on addressing key implementation barriers that extend beyond policy formulation, including challenges related to cost, training, calibration, and variability in real-world frying conditions.

3. Recommendations for Stakeholders

3.1 For Food Service Operators

Food service operators should treat Total Polar Compounds (TPC), measured via portable devices where accessible, as one of several indicators of oil quality rather than a standalone metric. TPC assessment should be integrated with visual cues such as oil color, olfactory indicators like odor, and functional parameters including cooking performance. Operators are advised to seek oil-type-specific guidance from suppliers instead of assuming uniform applicability of the 25% threshold across all oils, given variability in degradation behavior. Maintaining structured oil usage logs—including batch numbers, frying start dates, and cumulative frying time—is essential for traceability and decision-making. Additionally, implementing systematic staff training on oil quality evaluation and disposal decisions is critical. Oils exceeding the 25% TPC threshold prescribed by the Food Safety and Standards Authority of India should be segregated and directed toward RUCO (Repurpose Used Cooking Oil)–compliant biodiesel conversion pathways.

3.2 For Regulatory Agencies and Policy Bodies

Regulatory authorities should prioritize the development and dissemination of clear training materials and operational protocols tailored for small and medium food service operators, ensuring practical understanding of the FSSAI 25% TPC threshold and its implementation. Establishing standardized calibration protocols for portable TPC devices, along with improving access to affordable reference oil standards, is necessary to enhance measurement reliability. Agencies should also provide oil-type-specific guidance or, at minimum, educate operators on variability across oil categories and appropriate interpretation of TPC values. Formal integration of TPC criteria into RUCO operational frameworks and routine food safety inspection systems will strengthen compliance. Furthermore, investment in district-level or subsidized laboratory testing facilities can support resource-constrained operators, while targeted awareness campaigns can improve adoption among street vendors and small restaurant owners.

3.3 For the Research Community

The research community should focus on conducting systematic and replicated studies on TPC accumulation across commonly used Indian frying oils—such as palm, groundnut, coconut, and blended vegetable oils—under realistic cooking conditions. Comparative validation studies between portable TPC meters and laboratory-based chromatographic methods are needed across different oils, temperature profiles, and device models to establish reliability benchmarks. Investigations into oil-specific TPC formation kinetics would support more nuanced regulatory recommendations. Additionally, cost–benefit analyses evaluating the economic feasibility of TPC monitoring relative to its public health and operational benefits are essential. Finally, there is a need to develop and field-test integrated decision-making frameworks that combine TPC with complementary indicators such as free fatty acids (FFA), peroxide value, and sensory evaluation for a more holistic assessment of frying oil quality.

3.4 Future Research Priorities

Significant research opportunities exist to strengthen evidence-based implementation of the FSSAI 25% TPC threshold:

1. **Oil-Specific TPC Kinetics:** Systematic studies across commonly used Indian oils (palm, groundnut, sunflower, coconut, refined blends) characterizing cumulative TPC accumulation and establishing oil-specific degradation curves.

2. **Device Validation:** Comparative studies validating portable TPC meters against laboratory chromatography across diverse oils, temperature ranges, and device models to establish reliability boundaries.

3. **Small-Scale Implementation:** Field intervention studies in street food operations and small restaurants testing effectiveness of training, decision-support tools, and accessible measurement alternatives.

4. **Supplementary Indicators:** Investigation of TPC in combination with free fatty acids, peroxide value, anisidine value, and sensory parameters to develop comprehensive quality assessment frameworks.

5. **Economic Feasibility:** Cost-benefit analyses comparing monitoring implementation costs with health benefits of improved oil quality and operational efficiency gains.

6. **Health Outcomes:** Studies investigating specific health implications (oxidative stress, inflammation) associated with consumption of foods prepared in oils at defined TPC levels. This research agenda would provide the evidence foundation necessary to translate the FSSAI 25% regulatory policy into effective field implementation across diverse Indian food service settings while maintaining scientific rigor and practical feasibility.

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