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CRITICAL REVIEWS OF 3-MCPDE DETECTION: ADVANCES IN ANALYTICAL TECHNIQUES

MUHAMMAD QAYYUM OTHMAN[1]*; MOHD HAFIZ ABU BAKAR[2]; NUR HIDAYAH AZEMAN[3]; NADHRATUN NAIIM MOBARAK[4] and AHMAD ASHRIF A BAKAR[1,3]*

ABSTRACT

3-monochloropropane-1,2-diol esters (3-MCPDE) are food processing contaminants formed primarily during the high-temperature refining of edible oils. Their potential carcinogenic effect has led to increasing concern among health authorities and consumers. Conventional detection methods such as gas-chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) provide high accuracy but are often costly, labour-intensive and unsuitable for rapid or on-site analysis. In recent years, alternative approaches including spectroscopic, electrochemical and optical biosensing techniques have emerged as faster and more accessible tools for 3-MCPDE detection. This review explores the formation pathways of 3-MCPDE and critically examines both traditional and emerging analytical techniques, comparing their performance, advantages and limitations. The integration of nanomaterials, data-driven models and sensor miniaturisation is also discussed as a promising direction toward developing portable, cost-effective tools for safer food production and regulatory compliance.

Keywords: chromatography, edible oil, electrochemical, optical sensor, spectroscopy.

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INTRODUCTION

In recent years, the occurrence of certain contaminants in edible oils, notably 3-monochloropropanediol-1, 2-diol esters (3-MCPDE), has raised significant health concerns. During the high-temperature of oil refining process, 3-MCPDE is a byproduct that occurs as processing impurities. The 3-MCPDE is categorised as a potential human carcinogen (Group 2B) by the International Agency for Research on Cancer (IARC) (2013). It is produced through the deodorisation process of oils and has been associated with the development of tumours in animal experiments.

Human exposure to these chemicals primarily arises from ingesting processed edible oils in diverse food products. Prolonged exposure, even at minimal levels, may contribute to the development of cancer and other harmful effects (Luch et al., 2012). The European Food Safety Authority (EFSA) has established threshold levels for 3-MCPDE. To minimise the danger of human exposure to contaminants in edible oil, it is necessary to implement stricter laws, testing methodologies; and processing control measures. Moreover, it is essential for food organisations to develop reliable ways to detect contaminants in edible oils and fats, boosting market and consumer confidence in their quality and authenticity. This need has been highlighted by study on adulterations in some edible oils and fats (Azadmard-Damirchi et al., 2015).

Ensuring the safety of edible oils requires analytical techniques to identify harmful contaminants, such as 3-MCPDE, which may exist throughout oil processing (EFSA, 2018). Established methods such as liquid chromatography-tandem mass spectrometry (LC-MS/MS) and gas

[1] Photonics Technology Laboratory,
Department of Electrical, Electronic and Systems Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia.

[2] Institute of Power Engineering,
Universiti Tenaga Nasional,
43000 Kajang, Selangor, Malaysia.

[3] Institute of Microengineering and Nanoelectronics,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia.

[4] Department of Chemical Sciences,
Faculty of Science and Technology,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia.

* *Corresponding author e-mail: p138421@siswa.ukm.edu.my, ashrif@ukm.edu.my*

chromatography-mass spectrometry (GC-MS) are highly sensitive and specific, well-suited for the analysis of both polar and nonpolar substances, respectively (Blumhorst et al., 2013; Cheng et al., 2017). However, the need for extensive sample preparation, complex instrumentation and hazardous solvents has driven study into alternative optical sensors. Compared to chromatographic methods, optical biosensors such as surface plasmon resonance (SPR) offer direct measurements with high accuracy in significantly less time without extensive sample processing (Mehrotra et al., 2016). Optical biosensors can often detect analytes label-free by directly monitoring the interaction between the target molecule and the sensor surface. Optical sensors continue to improve in sensitivity, reproducibility, and ease of fabrication (Mehrotra et al., 2016). They have the potential to serve as inexpensive first-line screening tools for early detection on-site, with chromatographic techniques reserved for in-depth confirmatory analysis. A rapid optical screening may enable cost-effective, on-site monitoring of carcinogens in edible oils (Bhatti et al., 2022).

This article will critically review various techniques to detect 3-MCPDE in edible oils. It will discuss the detection of contaminants by using technological advancements in optical sensors. This review has been organised into a few sections to give readers a complete understanding of detecting carcinogenic in edible oils in the scope of optical sensors. The first section will highlight contamination sources in edible oils. It will focus on the formation of contamination and how it can affect human beings. It will cover the existing method to detect contamination in edible oils in the following section. The following section discusses the sensitivity of conventional methods, highlighting both their advantages and limitations. The final section briefly summarises emerging techniques for detecting contamination in edible oils. This study provides an in-depth review of emerging techniques, including their advantages, principles and sensitivities, compared to current techniques in the biosensor area for carcinogen detection in edible oil.

CONTAMINATION SOURCES IN EDIBLE OIL

The way edible oils are processed can negatively impact their appearance, flavour, shelf life and safety (MacMahon et al., 2013b). When the oil and its constituents undergo refining at elevated temperatures, certain lipid components are subjected to undesirable chemical transformations. One of the concerns is the generation of contaminants, like 3-MCPDE, which occur primarily during the deodorisation stage of heat-induced processes typically at temperatures exceeding 200°C in the presence of steam and, often, chlorine sources. Recent investigations have revealed that subjecting meals containing fat and salt to high-temperature processing with the addition of chlorine can produce a substance called 3-MCPDE (Marry & Steinmaus, 2011).

Free 3-MCPD comprises three carbon atoms, it contains a chlorine atom and two hydroxyl groups and the chemical formula representing 3-MCPD is $C_3H_7ClO_2$. According to EFSA Panel on Contaminants in the Food Chain (CONTAM) (2016), palm oil and palm-based fats contained an average 3-MCPDE concentration of 2,912 µg/kg, approximately four times higher than the 668 µg/kg reported for normal-fat margarine (EFSA CONTAM Panel, 2016). The 3-MCPDE has been linked to food processing contamination in a variety of types of food and ingredients since 1980, including edible oils that have been refined (Cheng et al., 2017). Globally, 3-MCPDE in refined edible oils has sparked rising concerns about food safety. According to a report, the synthesis of 3-MCPDE is primarily influenced by chloride, acylglycerols, pH, temperature and time (Kuntom et al., 2006). 3-MCPDE can be formed through acid hydrolysis, heat processing and oil processing with chlorine (Jędrkiewicz et al., 2016). *Figure 1* illustrates the representative chemical structures of chloropropanol contaminants and their ester derivatives, including 3-MCPD, 2-MCPD, 1,3-DCP, 3-MCPD diesters and 3-MCPD monoesters.

The formation of monochloropropanediols (MCPDs) and their esters has been reported as a process induced phenomenon during the refining of certain vegetable oils, including palm oil, under specific processing conditions. These compounds are primarily generated during the deodorisation step, which is conducted at high temperatures, typically above 225°C in the presence of steam to remove free fatty acids, volatile odour compounds and pigments (Destaillats et al., 2012a; Sulin et al., 2020). The presence of hydrogen chloride (HCl) during deodorisation does not arise from intentional addition but from *in situ* formation, typically caused by the high-temperature breakdown of residual organochlorine substances derived from previous processing stages, or it may arise from trace chlorinated materials introduced via water treatment chemicals such as ferric or magnesium chlorides or certain acid activated bleaching clays used in earlier stages of processing (Shimizu et al., 2012).

Under these high-temperature and mildly acidic conditions, lipid precursors such as mono and diacylglycerols undergo nucleophilic substitution reactions with available chlorine donors, leading to the formation of MCPD esters. Among these, 3-MCPDE are recognised as the

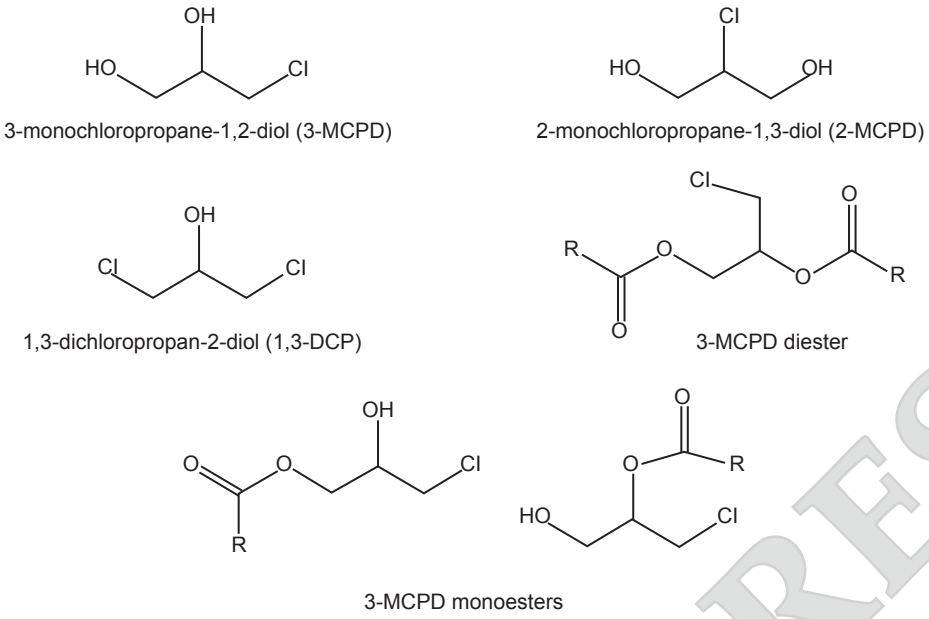


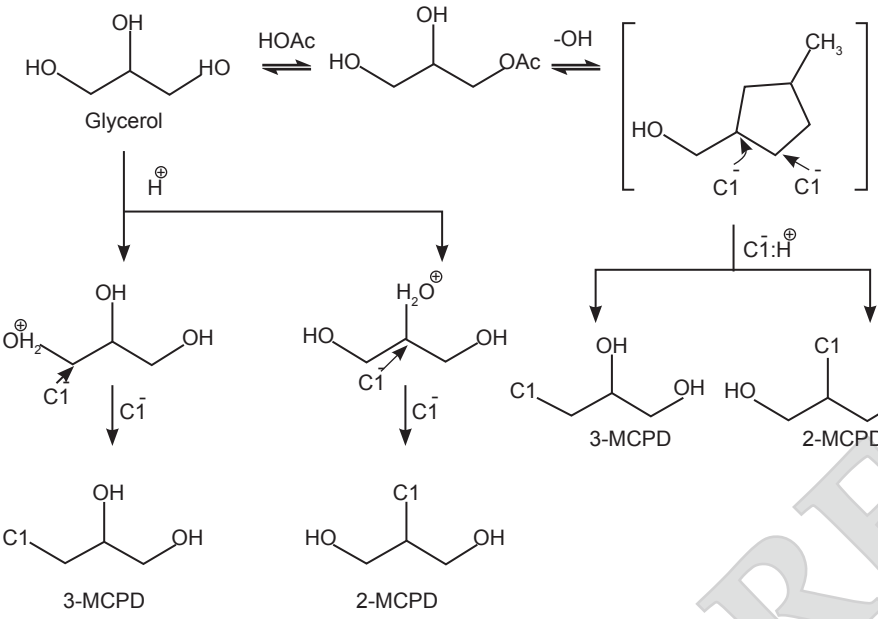
Figure 1. Representative chemical structures of chloropropanol contaminants and their ester derivatives commonly found in edible oils. These include 3-monochloropropane-1,2-diol (3-MCPD), 2-monochloropropane-1,3-diol (2-MCPD), 1,3-dichloropropane-2-diol (1,3-DCP), 3-MCPD diesters and 3-MCPD monoesters

predominant species detected in refined oils. Free 3-MCPD itself is typically present at much lower levels in the oil but can be released from its esterified forms through hydrolysis during gastrointestinal digestion (Destaillats et al., 2012b; Shimizu et al., 2012). This mechanistic understanding underscores that the occurrence of 3-MCPDE is associated with specific combinations of processing parameters, namely high temperature, the presence of chlorine sources and the availability of susceptible lipid intermediates, rather than being an inevitable outcome of all palm oil refining operations.

Shimizu et al. (2012) reported that partial acylglycerols are less likely to form triacylglycerol compared to 3-MCPDE. In addition, cooking and frying produce partial acylglycerols due to heat and steam (Hamlet et al., 2011). Other than that, chlorine, particularly in its inorganic form, becomes part of palm oil through various pathways, including its cultivation and extraction processes. Cultivation methods, which often utilise chloride salt-containing fertilisers and pesticides, along with the significant water volumes employed during oil extraction, contribute to this presence (Blumhorst et al., 2011).

Furthermore, the necessity of water for leaching soluble impurities and metallic salts during palm oil processing can introduce chlorinated compounds, given that iron (III) chloride is a common coagulant in water treatment. Nagy et al. (2011) have identified both inorganic and organic chloride varieties within palm oil. While inorganic chlorides stem from substances like ferric, ferrous, magnesium and calcium chlorides, organic chlorides naturally arise from the plants' inherent metabolic processes that are crucial for their development (Nagy et al., 2011). High temperatures during deodorisation might cause chlorine release, which can produce 3-MCPDE and other compounds (Matthäus et al., 2011). As shown in *Figure 2*, glycerol can undergo transformation into free 3-MCPD and 2-MCPD when exposed to high temperature and chloride ions during deodorisation.

More recent studies have expanded this mechanistic framework, confirming that the convergence of chlorine species, glyceride intermediates and deodorisation intensity dictates MCPDE levels rather than temperature alone. For instance, a nationwide Malaysian survey showed that 3-MCPDE and glycidyl esters (GE) varied significantly across regions and refineries, correlating with both total chlorine in crude palm oil (3.1–8.7 mg/kg) and refinery practices where refined palm olein contained the highest contaminant levels, while stearin fractions showed lower partitioning (Razak et al., 2019). Industrial-scale trials further revealed that simple interventions such as crude palm oil (CPO) washing with hot water could remove up to 85% of total chlorine and subsequently halve 3-MCPDE formation during refining, although GE levels remained tied to diacylglycerol (DAG) content and deodorisation temperature (Ramli et al., 2020). These results validate earlier laboratory findings and highlight the importance of addressing chlorine precursors at the mill stage.



Source: Collier et al. (1991).

Figure 2. Proposed formation pathways of 3-monochloropropane-1,2-diol (3-MCPD) and 2-monochloropropane-1,3-diol (2-MCPD) from glycerol under high-temperature processing in the presence of chloride ions and acidic conditions.

Complementary mitigation strategies including optimised degumming and bleaching, dual-stage deodorisation, enzyme/adsorbent treatments and post-refining have been evaluated, with varying success (Tivanello et al., 2021). 3-MCPDE remains the dominant contaminant in refined oils and reiterated the dual role of DAG as both a precursor to GE and an indirect driver of MCPDE, reinforcing that refining steps prior to deodorisation (water degumming, neutralisation, selection of bleaching earth) critically shape the contaminant profile (Ozluk et al., 2024). Importantly, large-scale commercial implementation in Malaysia has demonstrated that, with effective precursor removal and process optimisation, refined palm oil meeting European Commission limits (≤2.5 mg/kg for 3-MCPDE; ≤1.0 mg/kg for GE) is achievable (EFSA CONTAM Panel, 2016; Ramli et al., 2020).

Taken together, the integrated evidence from classical mechanistic studies (2011-2012) through large-scale surveys (2019) and mitigation trials (2020-2024) underscores that 3-MCPDE formation is not inevitable but a consequence of specific precursor process interactions. This understanding forms the basis for current industry efforts to refine palm oil with reduced contaminant loads while balancing product quality and regulatory compliance.

The main organ affected by 3-MCPDE is the kidney, as reported by the Joint FAO/WHO Expert Committee on Food Additives (JECFA). Prolonged intake of this substance leads to kidney damage, specifically nephropathy, tubular hyperplasia and adenomas (JECFA, 2011). The 3-MCPD has been categorised (IARC, 2013) as a potential human carcinogen in category 2B. Hence, the European Commission has identified two primary objectives to overcome 3-MCPDE by decreasing the quantities of 3-MCPDE through measures implemented by food business operators (Foster et al., 2009) and to assess potential maximum levels of 3-MCPDE in food products (Albuquerque et al., 2017; Larsen et al., 2009). In 2013, EFSA released a report that identified the food groups that primarily contribute to the intake of these harmful substances. The dangerous chemicals were significant in margarine and vegetable oils (EFSA, 2013). 3-MCPDE are common food processing contaminants and lipase degrades them *in vivo* into free 3-MCPD (MacMahon et al., 2013a).

Experimental animals fed large dosages of 3-MCPDE over lengthy durations developed renal hyperplasia and reproductive organ tumors (Sun et al., 2013). Refined palm oil, commonly used in heat-processed foods (Küsters et al., 2011) and baby formula (Zelinková et al., 2009), has been shown to contain 3-MCPDE (Bakhiya et al., 2011). As reported by El Ramy et al. (2007), exposure to 3-MCPDE may cause nephrotoxicity, raising concerns about food contaminants. 3-MCPDE or its metabolites such as glycidol have been investigated for their genotoxic potential (El Ramy et al., 2007).

Recent risk assessments have substantiated earlier toxicological evidence, with the EFSA CONTAM Panel (2016, 2018) designating the

kidney and testes as the principal target organs of concern and setting a tolerable daily intake (TDI) of 2 µg/kg body weight per day for free 3-MCPD and its esterified forms. Razak et al. (2019) found measurable 3-MCPDE and GE in Malaysian palm oil products, with refined olein showing the highest concentrations, underscoring regional and processing variability. Ramli et al. (2020) demonstrated in commercial-scale trials that reducing chlorine content in CPO (via hot water washing) significantly lowered 3-MCPDE formation during refining, although GE remained elevated due to DAG precursors. More recently, Ozluk et al. (2024) reviewed toxicological evidence and reaffirmed 3-MCPDE as a major concern for infant and young children's exposure, given the high reliance on vegetable oils in infant formula products. They emphasised that while mitigation has reduced levels over the past decade, refined palm oils remain a dominant contributor to overall dietary intake.

Although palm oil is often highlighted for its higher 3-MCPDE and GE levels, these contaminants are also present in other refined oils. Soybean, canola, sunflower, corn, rice bran and peanut oils generally contain <1–3 mg/kg, while walnut and hazelnut oils can reach up to 19 mg/kg, and fish oils show a wide range from <0.1–34 mg/kg. Such variation reflects differences in fatty acid composition (FAC), DAG content and refining conditions. Razak et al. (2019) further confirmed their presence in commercial cooking oils, including blends with canola, soybean, sunflower and sesame oils.

Large-scale mitigation trials show that while CPO washing effectively reduces 3-MCPDE in palm oil, similar principles apply to other seed oils. GE formation remains strongly linked to DAG content and high deodorisation temperatures (>230°C), highlighting that 3-MCPDE and GE formation are a widespread issue across edible oil refining, not limited to palm oil (Ramli et al., 2020). Consequently, understanding the occurrence, formation pathways and mitigation strategies of these contaminants requires a broader perspective that encompasses multiple vegetable oils and fats beyond palm oil (EFSA CONTAM Panel, 2016).

Collectively, both older and newer studies converge on the conclusion that 3-MCPDE are not only widespread food processing contaminants but also substances of toxicological concern due to their renal and carcinogenic effects. Ongoing study thus continues to guide regulatory limits and industrial mitigation strategies, ensuring that consumer exposure, particularly in vulnerable groups, remains within safe thresholds. Due to possible carcinogens from 3-MCPDE, some countries have set regulations on 3-MCPDE (Laval, 2023). The European Union (EU) regulation sets the maximum level of a 3-MCPDE to be 1.25 ppm from various edible oils. For other countries such as China, Canada, Indonesia and Malaysia, the limits for 3-MCPDE are 0.40–1.00, 1.00, 2.50 and 1.25 ppm, respectively. *Table 1* summarises the regulatory limits of detection (LOD) for 3-MCPDE across different countries.

TABLE 1. REGULATORY LIMITS OF DETECTION (LOD) FOR 3-MCPD AND ITS ESTERS IN VARIOUS FOOD PRODUCTS ACROSS DIFFERENT COUNTRIES

Country	Sample	LOD (ppm)	Reference
European union	Edible oils	1.25	Commission Regulation (EU) 2020/1322 (2020)
China	Solid condiment Liquid condiment	0.40 1.00	NHFPC and CFDA (2018)
Canada	Soy sauce	1.00	Government of Canada (2020)
Indonesia	Palm oils	2.50	Sawit (2020)

Note: National Health and Family Planning Commission of the People's Republic of China & China Food and Drug Administration (NHFPC & CFDA).

METHODS FOR DETECTING CARCINOGEN COMPOUNDS

Chromatography: Benchmark Techniques

Chromatography is a scientific procedure employed to separate each component in the mixture by utilising variations in their attraction to two distinct phases, a stationary phase and a moving phase, as stated by Grinberg and Sonia (2019). The theory behind the approach is that the various components of the mixture will interact differently with the stationary surface as the mobile phase passes through the stationary phase, causing each component to move at a distinct rate (Fanali et al., 2017). Examples of chromatography are high-performance liquid chromatography (HPLC), liquid chromatography (LC), gas chromatography (GC) and others.

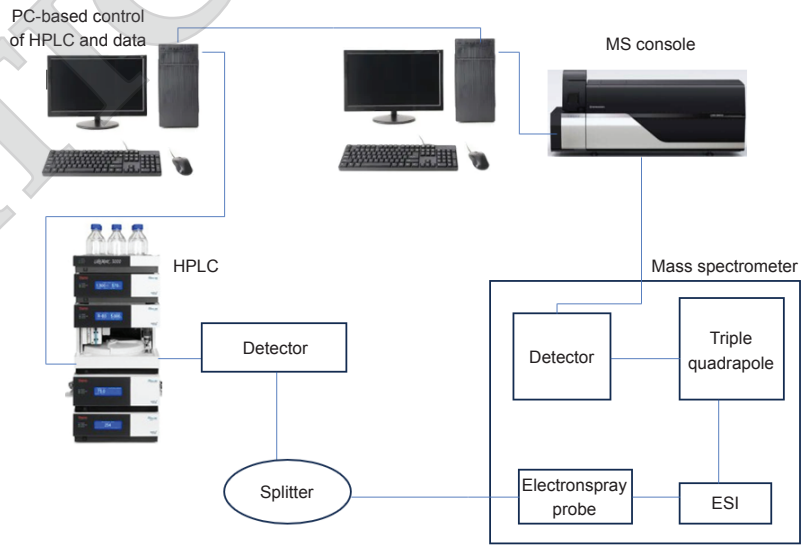
Reflecting this benchmark status, numerous studies over the past decade have applied chromatography for the precise quantification of 3-MCPDE. Reports from MacMahon et al. (2013c) demonstrated the presence of free 3-MCPD and 2-MCPD in edible oils, raising concerns due to their classification as potential human carcinogens (Macmahon et al., 2013c). This concern is supported by toxicological evidence, as *in vivo* studies have shown that unbound free 3-MCPD can induce carcinogenesis in the renal and reproductive systems of rats (Cho et al., 2008). For example, the target chemicals, fatty acid diesters

of 2-MCPD and 3-MCPD were extracted from oil matrices using a two-step solid-phase extraction (SPE) process where LC-MS/MS with electrospray ionisation (ESI) technique is used to quantify the chemicals. The validity of the approach has been verified for 28 various 3-MCPD diesters found in edible oils. These diesters are produced from fatty acid derivatives. The assessment of 3-MCPD diesters utilised an external calibration curve, with a maximum limit of quantification (LOQ) of 30 ppb across three oil matrices. Mean recoveries and relative standard deviations (RSDs) reported ranged from 88% to 118% and 2% to 16%, respectively. This method requires using a solvent solution with selectivity, such as the one used to analyse 3-MCPD monoesters, allowing for sample preparation for both analyses.

In other studies by Hori et al. 2012 devised a technique employing liquid chromatography time-of-flight mass spectrometry (LC/TOF-MS) for the analysis of 3-MCPDE in edible oils. Analytes were extracted by SPE and eluted using a gradient mobile phase of methanol and sodium formate on a Waters UPLC C18 chromatography column. The system displayed great sensitivity (0.86 ng mL^{-1} for 3-MCPD monoesters and 0.22 ng mL^{-1} for 3-MCPD diesters) when selected ion monitoring mode was employed to identify the sodiated adducts of the target chemical substances. *Figure 3* illustrates a schematic diagram of an LC-MS/MS system with ESI used for the detection of 3-MCPDE.

Razak et al. (2012) evaluated using the acidic transesterification method and using GC with Mass Selective Detector (GC-MSD) to detect 3-MCPDE in edible oil based on the Federal German Institute for Risk Assessment Method. In their study, the method achieved a LOD of 0.25 mg/kg and a LOQ of 0.50 mg/kg, demonstrating sufficient sensitivity for monitoring trace levels of 3-MCPDE. Trace levels of 3-MCPDE were found in bleached oils, while none were detected in crude oils. Significant quantities of 3-MCPDE are present in deodorised or extensively refined oils, whereas the concentration in palm oil products varies from -0.25 to 5.77 mg/kg (Razak et al., 2012). To precisely target the analysis of fatty acid esters of 3-MCPD in edible oils, researchers developed a method using ultra-high performance liquid chromatography-triple quadrupole mass spectrometry (UHPLC-MS/MS) in conjunction with matrix solid-phase dispersion (MSPD) extraction for increased sensitivity and selectivity (Li et al., 2015). It is reported that the LOD of 3-MCPDE was 0.0001–0.0200 mg/kg. In this study, the direct dilution and injection method for removing and cleaning 3-MCPDE from contaminated oil samples should have fewer matrix interferences from MSPD cleanup (Crews et al., 2013).

Additionally, when compared with the SPE method, which typically requires at least 30 min to complete, the cleaning process for a single sample in this study could be completed in only about 3 min. This demonstrates a clear improvement in efficiency and shows the potential for faster sample handling. Previous studies, such as those by Yoshioka and Ichihashi (2008) and Wardencki et al. (2009), have reported that conventional analytical techniques are widely applied for contaminant



Source: Patel et al. (2010).

Figure 3. Schematic representation of a (LC-MS/MS) system for 3-MCPD and ester analysis, showing the integration of high-performance liquid chromatography (HPLC) separation with electrospray ionisation (ESI) and triple quadrupole mass spectrometry for sensitive detection.

analysis in food processing. These advances highlight chromatography's continued role as the most dependable confirmatory tool. *Table 2* below highlights the summary of chromatography methods on 3-MCPDE in oils. However, its inherent drawbacks such as laborious workflows, high operating costs and the need for skilled personnel, have created a strong demand for faster, more accessible alternatives. This need has directed attention toward spectroscopic techniques, which aim to complement chromatography by offering rapid, non-destructive analysis with less intensive sample preparation. As highlighted by Lee et al. (2013), these challenges create a significant gap in developing rapid, cost-effective and fieldready detection methods for the food industry.

EMERGING SENSING TECHNIQUES FOR CONTAMINANT DETECTION

The challenge of detecting contaminants, particularly carcinogens like 3-MCPDE in edible oils, necessitates continuous advancements in analytical methodologies. Conventional chromatographic methods, often coupled with mass spectrometry, have long served as the gold standard for accurate quantification. However, many of these chromatographic approaches were developed over a decade ago and remain labour-intensive, requiring lengthy sample preparation, specialised equipment and skilled personnel. These limitations highlight the need to move beyond traditional protocols toward more rapid, cost-effective and field-deployable alternatives. In this context, spectroscopy-based methods and other advanced sensing platforms are increasingly recognised as promising tools for real-time detection and monitoring of 3-MCPDE and related contaminants.

Spectroscopy: Bridging Speed And Accessibility

Building on the strengths and limitations of chromatography, spectroscopic techniques have gained prominence as faster, less destructive alternatives. These methods analyse how electromagnetic radiation interacts with matter to generate unique spectral fingerprints that can be used to identify compounds and determine their concentrations (Crocombe et al., 2018; Kellner et al., 1998; Smith et al., 2011). By exploiting different regions of the electromagnetic spectrum, techniques such as electron spin resonance (ESR), Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR) and UV-Vis spectroscopy provide rapid detection with reduced sample preparation and lower

TABLE 2. SUMMARY OF CHROMATOGRAPHY-BASED METHODS FOR THE DETECTION OF 3-MCPD ESTERS (3-MCPDE) IN EDIBLE OILS, HIGHLIGHTING SAMPLE PREPARATION, ANALYTICAL TECHNIQUES AND DETECTION RANGES

Detection	Sample preparation	Contaminant	Range of detection (µg/kg)	Reference
LC-TOFMS	3-MCPD monoester: SPE with C18 and SI cartridge; 3-MCPD diesters: SPE with SI cartridge	3-MCPDE	-	Zwagerman et al. (2019)
LC-TOFMS, ESI, sodium ion adducts	Direct dilution and injection	3-MCPDE	100–1,400	Haines et al. (2010)
LC-TOFMS, ESI, sodium ion adducts	Liquid/Liquid partition by hexane and acetonitrile, SPE with SI and C18 cartridge	3-MCPDE	-	Hori et al. (2012)
LC-MS/MS, APPS	Sample cleanup on SI SPE cartridge	3-MCPDE	-	MacMahon et al. (2013a)
LC-OrbitrapMS, ESI, ammonium ion adducts	3-MCPD monoester: Aminopropyl SPE cartridge; 3-MCPD diesters: SI SPE cartridge	3-MCPDE	2–5	Moravcova et al. (2012)
DART-OrbitrapMS, ammonium ionadducts	3-MCPD monoester: Aminopropyl SPE cartridge; 3-MCPD diesters: SI SPE cartridge	3-MCPDE	40–174	Moravcova et al. (2012)
LC-MS/MS, ESI, ammonium ion adducts	Two-step SPE procedure: C18 and SI	3-MCPDE	10–60	Macmahon et al. (2013c)
LC-MS/MS, ESI, ammonium ion adducts	Two-step SPE procedure: C18 and SI	3-MCPDE	14–71	Yamazaki et al. (2012)
HPLC-ELSD	Samples extracted by acetonitrile	3-MCPDE	3.43	Zhou et al. (2014)
UHPLC-MS/MS, ESI, ammonium ion adducts	Matrix Solid Phase Dispersion (MSPD) Extraction	3-MCPDE	0.1–2.0	Li et al. (2015)

operational costs. Recent applications have shown that these approaches are capable of detecting 3-MCPDE and its precursors in edible oils, for example, ESR for radical species (Zhang et al., 2013; Zhao et al., 2016), FTIR coupled with chemometrics and machine learning for quantitative predictions (Goh et al., 2019; Wang et al., 2025), NMR for absolute quantification without reference standards (Ji et al., 2016; Mahiran et al., 2023) and UV-Vis for affordable, practical screening (Aka et al., 2022).

Previous studies by Zhang et al. (2013) and Zhao et al. (2016) have provided significant insights into the formation mechanism of 3-MCPDE during food processing. Both study groups demonstrated that 3-MCPDE are formed predominantly via a free radical-driven pathway, which is notably facilitated under conditions of high temperature and low moisture. Zhang et al. (2013) employed ESR spectroscopy combined with spin-trapping agents to detect free radicals generated in vegetable oil heated to 120°C. Their results showed a clear increase in radical concentration corresponding to extended heating times. Complementary FTIR spectroscopy analyses indicated the active participation of ester carbonyl groups in the radical-mediated reaction. Similarly, Zhao et al. (2016) identified free radicals and proposed a detailed mechanistic pathway involving cyclic acyloxonium intermediates derived from monostearoyl glycerol. Collectively, these studies underscore the pivotal role of free radical species in the thermal formation of 3-MCPDE, advancing the understanding of contaminant generation in edible oils during processing.

Goh et al. (2019) introduced an innovative, rapid and non-destructive method for assessing MCPDE in palm-based cooking oil. Using attenuated total reflection fourier transform infrared (ATR-FTIR) spectroscopy combined with chemometric models including PLSR, neural networks (nnet, avNNET), random forest (RF) and Cubist, they demonstrated an effective alternative to traditional GC-MS analysis. Notably, the cubist model and a consensus approach yielded high prediction accuracy for total MCPDE content. The identification of key FTIR wavenumbers associated with MCPDE highlights the technique's potential. This integrated ATR-FTIR and chemometric approach offers a promising, flexible solution for quality control in the edible oil industry (Goh et al., 2019).

As reported by Wang et al. (2025), they addressed the urgent need for a non-destructive and highly accurate method to quantify 3-MCPDE in fried oil, avoiding the labour-intensive pretreatment required by conventional techniques. They developed a method that combines FTIR spectroscopy with a convolutional neural network (CNN) model. A key innovation was their use of a stepwise hybrid preprocessing strategy (NL-SGS-D_2), which significantly reduced background noise and improved the CNN's feature extraction performance. This enhanced method achieved excellent results, with a determination coefficient (R^2) of 0.9982 and root mean squared error of calibration (RMSEC) of 0.0181, marking a 16% improvement over models without preprocessing. Importantly, the method reached an LOD of 0.36 µg/g and LOQ of 1.10 µg/g, meeting the strict EU safety standards for 3-MCPDE in edible oils. Overall, the study presents a highly effective and practical tool for real-time quality monitoring in the edible oil industry, offering a reliable alternative to traditional analytical methods (Wang et al., 2025).

Moreover, Aka et al. (2022) recently investigated the presence of 3-MCPDE in 11 commonly consumed food products in Côte d'Ivoire. The team used a dual detection method that combined UV-Vis spectroscopy and electrochemical sensors based on cysteine-modified silver nanoparticles (Cys-AgNPs). Among the samples tested, palm oil and tuna frying oil had the highest levels of 3-MCPDE, reaching up to 1,773 and 1,280 µg/kg, respectively. Both detection methods showed strong consistency, though UV-Vis was slightly more sensitive. The findings emphasise the importance of monitoring 3-MCPDE levels in edible oils and demonstrate the value of using practical, cost-effective tools for improving food safety (Aka et al., 2022).

Furthermore, Ng et al. (2023) demonstrated that quantitative NMR (qNMR) spectroscopy is a powerful tool for detecting organochlorines, which are known precursors to 3-MCPDE in edible oils. Unlike traditional chromatographic methods, qNMR offers direct and accurate quantification without needing similar reference standards, as it measures the nuclei of molecules themselves. NMR spectroscopy allows detailed molecular characterisation including structure, functional groups and dynamics in both solid and liquid states. Its quantitative capability is based on the direct correlation between peak area and the number of nuclear spins, enabling accurate, absolute concentration measurements (Jaki et al., 2020; Simmler et al., 2014). In their study, qNMR effectively distinguished between different types of edible oils such as refined olive oil, sunflower oil, palm super olein and crude palm oil. Impressively, the method achieved a limit of detection of 0.14 µg/kg, showing its high sensitivity for monitoring organochlorine contaminants in food products (Ng et al., 2023).

Spectroscopic techniques like ATR-FTIR, qNMR, ESR and UV-Vis have shown great promise in detecting 3-MCPDE and its precursors due to their impressive sensitivity. However, working with edible oils presents its own set of challenges as the complex oil matrix often produces interfering signals that can mask the unique spectral fingerprint of 3-MCPDE, making accurate measurements more difficult. Additionally, these methods typically require advanced data processing techniques (such as noise reduction and baseline correction), which adds complexity and can affect reproducibility under variable conditions.

Techniques such as qNMR and ESR, while highly sensitive, rely on expensive instrumentation and skilled expertise, limiting their practical application in routine industrial settings. Moreover, despite their low detection limits, spectroscopic approaches often struggle to balance sensitivity with specificity in complex oil matrices, where overlapping signals may necessitate additional sample preparation or enrichment. *Table 3* summarises recent spectroscopic methods reported for 3-MCPDE detection and their corresponding limits of detection, highlighting both their promise and their constraints. Overall, while spectroscopy offers faster and less destructive alternatives to chromatography, persistent challenges with matrix effects, data processing and portability underscore the need for more robust and practical sensing strategies. These limitations have driven the development of advanced electrochemical and optical biosensors aimed at achieving real-time, on-site detection.

ADVANCED TECHNIQUES: TOWARD ON-SITE DETECTION

The remaining gaps in both chromatography and spectroscopy particularly the lack of portability and challenges in handling complex oil matrices have accelerated the development of advanced electrochemical and optical sensors. Electrochemical sensors enhanced with molecular imprinted polymer (MIPs) and nanomaterials, as well as optical platforms such as surface plasmon resonance (SPR) and nanoparticle-based colourimetry, aim to provide rapid, real-time and field-ready detection of 3-MCPDE. These methods represent a progressive step in analytical development, advancing from the confirmatory precision offered by chromatography and the rapid accessibility provided by spectroscopy toward practical, on-site monitoring. Collectively, they constitute a complementary toolkit for ensuring the quality and safety of edible oils.

Electrochemical Sensors

Among these advanced approaches, electrochemical sensors have attracted significant attention because they combine portability with high sensitivity and cost-effectiveness, making them well suited for routine screening applications. Recent electrochemical sensors for detecting 3-MCPDE leverage molecular imprinting and nanomaterial enhancements to offer rapid, cost-effective and highly sensitive detection. For example, Yaman et al. (2021) fabricated a disposable sensor by electropolymerising an overoxidised polypyrrole (oPPy) layer using 3-MCPDE as the template directly onto a graphene oxide-modified pencil graphite electrode. By controlling the solution pH and employing electrochemical impedance spectroscopy (EIS) with a redox probe, they confirmed that the molecularly imprinted cavities afford three-dimensional recognition of the target, resulting in a linear detection range of 2.00–500.0 nM and a detection limit of 1.82 nM. Another approach integrated a Fe-MIL-88 MOF with an electrochemical MIP on gold screen-printed electrodes, yielding linear detection ranges of 0.05–0.50 μM with detection limits as low as 0.01 μM under optimised conditions (Özyurt et al., 2025).

In another study, Munawar et al. (2021) used synthetic antibody-like MIPs that not only acted as a selective solid-phase extraction tool but also as a sensing element in electrochemical systems, achieving recoveries above 90% and detection

TABLE 3. SUMMARY OF SPECTROSCOPIC APPROACHES APPLIED FOR THE DETECTION OF 3-MCPD ESTERS (3-MCPDE), INCLUDING REPORTED LIMITS OF DETECTION (LOD)

Techniques	LODs	Reference
Fourier transform infrared (FTIR) resonance	-	Zhang et al. (2013); Zhao et al. (2016)
Attenuated total reflection fourier transform infrared (ATR-FTIR)	-	Goh et al. (2019)
Fourier transform infrared resonance (FTIR) with a convolutional neural network (CNN) model	0.36 μg/g	Wang et al. (2025)
UV-Vis spectroscopy with electrochemical detection based on cysteine-modified silver nanoparticles (Cys-AgNPs)	1,773 and 1,280 μg/kg	Aka et al. (2022)
NMR (qNMR) spectroscopy	0.14 μg/kg	Ng et al. (2023)

limits in the 2.5 µg/kg range. In addition, Sun et al. (2014) advanced the field further by fabricating a sensor based on a self-assembled p-aminothiophenol/3-MCPDE layer on gold nanoparticle-modified glassy carbon electrodes after electropolymerisation and template removal, the resulting MIP film yielded detection limits as low as 3.8×10^{-18} mol L^{-1} and excellent recovery rates in spiked soy sauce samples.

Similarly, sensors based on cysteine-coated silver nanoparticles and on graphene oxide-modified pencil graphite electrodes demonstrated low detection limits (2.40 ng/mL and 1.82 nM, respectively) with high specificity in complex matrices such as smoked mackerel, palm oil and soy sauce. Collectively, these studies show that combining molecular imprinting with advanced electrode modifications provides a robust, portable alternative to conventional methods like GC-MS for routine 3-MCPDE monitoring in food safety applications (Martin et al., 2021a).

Despite their promising sensitivity and rapid response, these electrochemical sensors for 3-MCPDE suffer from several limitations. Many of the sensors require intricate, multi-step fabrication processes such as electrode modification, self-assembly of recognition layers, nanomaterial deposition and electro polymerisation that complicate production and can hinder reproducibility on a large scale. Additionally, sensor performance is often sensitive to environmental factors like temperature and humidity, which can affect long-term stability and reliability in real-world applications. In some cases, the extraordinarily low detection limits, while scientifically impressive, may require impractical sample dilution or raise dynamic range concerns relative to regulatory thresholds. Moreover, optimal performance of these sensors necessitates careful and labour-intensive tuning of numerous parameters for example film thickness, electrode loading, and analyte-to-monomer ratio, posing challenges for scalability and consistent industrial production. *Table 4* provides a comparative summary of electrochemical sensor configurations reported for 3-MCPDE analysis, including molecularly imprinted polymer (MIP)-based and nanoparticle-enhanced systems.

Optical Techniques

Across existing methods, chromatography sets the benchmark for accuracy but is laboratory-bound and spectroscopy improves speed but is constrained by instrumentation needs. Unlike electrochemical sensors, which achieve impressive sensitivity through molecular imprinting and nanomaterial integration but often require complex fabrication and suffer from stability concerns while optical sensors rely on relatively straightforward nanoparticle functionalisation strategies, thereby positioning themselves as promising tools for on-site detection of 3-MCPDE in edible oils.

Faramitha et al. (2023) reported that refined palm oil products may contain trace levels of 3-MCPDE, a process induced contaminant considered potentially carcinogenic when consumed frequently over time. Existing analytical methods for 3-MCPDE detection, such as GC-MS and LC-MS/MS, though highly sensitive, require complex instrumentation, laborious sample preparation and expert operation, making them unsuitable for routine or onsite monitoring. Consequently, there is a critical need for a rapid and reliable detection approach. In this context, Faramitha et al. (2023) developed a colourimetric sensing strategy using glutathione-functionalised gold nanoparticles (GSH-AuNPs), in which 250 µL of 0.02 M GSH was used to produce stable rubyred GSH-AuNPs exhibiting a SPR band at 520 nm. The UV-Vis absorbance of the GSH-AuNPs decreased proportionally with increasing 3-MCPDE concentration in the oil, indicating a clear detection mechanism (Faramitha et al., 2023). This sensing behaviour is consistent with the reaction mechanism proposed by Martin et al. (2021b), who demonstrated that the amine group of glutathione can substitute the chlorine atom of 3-MCPDE via

TABLE 4. COMPARATIVE SUMMARY OF ELECTROCHEMICAL SENSOR CONFIGURATIONS REPORTED FOR 3-MCPDE ANALYSIS

Electrochemical sensors	LODs	Reference
Electrochemical impedance spectroscopy (EIS)	1.82 nM	Yaman et al. (2021)
Fe-MIL-88 MOF with an electrochemical molecularly imprinted polymer (MIP)	0.01 µM	Özyurt et al. (2025).
Synthetic antibody-like MIPs	2.5 µg/kg	Munawar et al. (2021)
Self-assembled p-aminothiophenol/3-MCPD layer on gold nanoparticle-modified glassy carbon electrodes (MIPs)	3.8×10^{-18} mol L^{-1}	Sun et al. (2014)
Sensors based on cysteine-coated silver nanoparticles and on graphene oxide-modified pencil graphite electrodes (MIPs)	2.40 ng/mL and 1.82 nM	Martin et al. (2021a)

a nucleophilic substitution reaction, forming N-(2,3-dihydroxypropyl)-amino acid moieties on the AuNP surface (Martin et al., 2021b). Such a substitution process explains the optical changes observed in the GSH-AuNP system, thereby providing a mechanistic basis for the measurable response reported by Faramitha et al. (2023).

In parallel, efforts have been made to understand and minimise the formation of 3-MCPDE during refining. A study on a 200 kg batch refining plant evaluated the role of degumming and bleaching, showing that phosphoric acid degumming (0.1%) combined with acid-activated clays yielded the highest levels of 3-MCPDE (3.89 mg/kg), while water degumming with natural bleaching clays resulted in significantly lower levels (0.25 mg/kg), albeit with slightly reduced oil quality. A strong correlation between bleaching earth acidity and ester formation was observed, suggesting that refining conditions significantly influence contaminant levels. Importantly, Ramli et al. (2011) demonstrated that by optimising processing parameters such as reducing acid dosage according to crude oil characteristics, selecting appropriate bleaching agents, or implementing neutralisation prior to deodorisation 3-MCPDE formation can be effectively mitigated without compromising oil quality (Ramli et al., 2011). These collective findings emphasise that while study such as Faramitha et al. (2023) is advancing rapid detection tools like GSH-AuNPs, concurrent process optimisation studies, play a crucial role in counteracting 3-MCPDE formation. Together, these approaches contribute to ensuring both the safety and the positive reputation of refined palm oil products.

Mahardika et al. (2023), in their study, introduced a user-friendly biosensor that uses cysteine-coated AgNPs for fast, colour-based detection of 3-MCPDE in cooking oils. The sensor works by exploiting the reactivity of cysteine's functional groups with 3-MCPDE, which triggers a noticeable colour change that can be easily measured using UV-Vis spectrophotometry. FTIR analysis confirmed that cysteine successfully binds to the AgNP surface evidenced by the disappearance of the S-H band and shifts in carboxyl group vibrations supporting the proposed substitution reaction with 3-MCPDE. The authors construct a calibration curve covering 0–5 ppm and applied the sensor to real samples, finding that new cooking oil contained about 2,828 µg/kg of 3-MCPDE, while used oil reached as high as 19,042 µg/kg, well above the European Commission's limit of 1,250 µg/kg (Mahardika et al., 2023).

In another study, Xu et al. (2024) described an optical fluorescence method for detecting 3-MCPD that capitalised on the quenching effect of this contaminant on a pyrocatechol-polyethyleneimine (PCh-PEI) polymer. In their approach, the fluorescence signal was measured under various conditions, and they found that at pH 8.5°C and 100°C, the polymer's fluorescence was best quenched by 3-MCPDE. Under these optimised conditions, the method showed a linear response over a range of 0.08–2.00 mg/L, with a detection limit as low as 0.06 mg/L ($r = 0.9974$). While these results highlight the capability of the optical method for rapid and sensitive detection, the requirement to operate at 100°C may limit its practical use in everyday food testing scenarios. Additionally, although the sensitivity is commendable, further validation in real food matrices is necessary to ensure that the technique remains robust when confronted with potential interferences present in complex samples (Xu et al., 2024).

In this study, the researchers introduced an innovative optical dosimeter based on a benzothiazole derivative to detect 3-MCPDE a food contaminant of serious concern. The method leverages the mechanism of fluorescence quenching when 3-MCPDE substitutes its chlorine atom with the amino group of barium titanate ($BT\text{-}NH_2$), the fluorescence of the system drops sharply. Impressively, the sensor responds within fours, exhibits excellent linearity, and achieves a low detection limit of 0.048 mg/L. Moreover, by incorporating an immobilised test strip, the system even allows for simple on-site visual analysis. While these optical features present a truly promising, cost-effective alternative to conventional chromatographic methods, some critical challenges remain. For instance, the long-term stability of the fluorescence signal in complex food matrices and its selectivity against structurally similar compounds need further evaluation (Zhao et al., 2025).

Each optical approach shows considerable promise, yet they come with their own challenges. For example, Faramitha et al. (2023) introduced a colourimetric sensor based on glutathione-modified gold nanoparticles that relies on changes in SPR at 520 nm. However, this technique is very sensitive to the glutathione concentration excess ligand, which can cause nanoparticle aggregation and complicate performance in complex oil matrices. Similarly, Mahardika et al. (2023) developed a Cys-AgNPs biosensor that produces a clear colour change upon binding 3-MCPDE. Despite its rapid response, further work is needed to confirm its reproducibility and efficacy when potential interferents in cooking oils are present. Xu et al. (2024) achieved highly sensitive detection using a fluorescence method based on a pyrocatechol-polyethyleneimine polymer, but the requirement to operate at 100°C and at an

exact pH limits its practicality for routine use. The benzothiazole-based dosimeter, which quenches fluorescence upon nucleophilic substitution with 3-MCPDE, shows ultrafast response and promising on-site visual detection, yet its long-term stability and selectivity against similar compounds remain questionable. *Table 5* below shows the summary of optical techniques for 3-MCPDE detection.

Early detection of 3-MCPDE in edible oils is vital to reduce the risk of exposure to this potentially carcinogenic compound, especially since its formation is influenced by various processing conditions. Traditional analytical methods are often complex and require expensive equipment and skilled technicians, making them less practical for routine monitoring. In contrast, modern biosensing techniques offer a promising alternative because of their high selectivity, sensitivity, simplicity and affordability (Dolatabadi & De La Guardia, 2014).

One particularly attractive approach is based on SPR, an optical phenomenon that occurs when light passing through a high-refractive-index prism experiences total internal reflection. This process interacts with a thin metal layer usually gold or silver and excites surface plasmons. The resulting changes in the reflected light spectrum provide a sensitive means of detecting biomolecular interactions, as the SPR angle shifts in response to variations in the refractive index of a biomolecular layer on the sensor surface (Fathi et al., 2018; Gupta et al., 2017; Mohammadzadeh-Asl et al., 2018).

Portable SPR sensors have achieved impressive detection limits in aqueous samples down to 20.0 ng/L for dichlorodiphenyltrichloroethane (DDT) and 0.1 ng/L for polychlorinated biphenyls (PCBs) (Hong et al., 2008; Mauriz et al., 2006). However, applying this technology to edible oils poses challenges. Edible oils are viscous, hydrophobic and contain complex mixtures that can interfere with optical signals. To overcome these hurdles, recent efforts have focused on integrating nanoparticles and carbon dots with SPR sensors. Nanoparticles enhance the local electromagnetic field, thereby boosting the plasmonic resonance, while carbon dots improve fluorescence coupling and signal contrast in challenging media.

Researchers have developed an innovative oil-based long-range SPR (LRSPR) sensor that can detect dinitrochlorobenzene (organochlorine) a known carcinogen in edible oils with outstanding sensitivity (0.0153 µg/L) and a very strong correlation (R^2 = 0.9536) between wavelength shifts and contaminant levels (Bakar et al., 2025). This same real-time, label-free detection ability makes SPR an ideal tool for tracking key biomarkers linked to kidney disease, including urea, creatinine, glucose, uric acid and dopamine, thus enabling early diagnosis and continuous health monitoring (Mulyanti et al., 2022).

In addition, Amirjani et al. (2018) highlighted the utilisation of silver nanostructures in SPR-based sensors for the detection of heavy metal ions. Silver nanoparticles, with their stronger plasmonic responses and lower dielectric losses compared to gold, prove to be excellent for real-time, cost-effective sensing. Their unique properties allow these sensors to work through different mechanisms such as aggregation/anti-aggregation, oxidation and morphological changes to detect toxic metals like mercury, lead, cadmium, cobalt and copper via colourimetric and spectroscopic methods. While these sensors can achieve sensitivity levels similar to those of conventional techniques like AAS and ICP-MS, there are still challenges, particularly regarding sensor stability, reproducibility and selectivity in complex sample matrices (Amirjani et al., 2018). Overall, the versatility of SPR with its various configurations (Kretschmann, Otto, optical fibre-based and localised SPR) and the enhanced performance afforded by integrating nanostructures offers a promising, robust platform for real-world, on-site monitoring across many applications.

Furthermore, an innovative strategy is to target the precursors of 3-MCPDE such as organic or inorganic chlorine-containing compounds before they transform into 3-MCPDE during high-temperature processing. Since compounds like chloropropanols, chlorinated fatty acids and acylglycerols are integral to the formation of 3-MCPDE, early detection of these precursors could offer critical insights and facilitate proactive measures. Tailoring the SPR sensor surface with selective receptors such as aptamers or antibodies can enhance specificity toward these chlorine-containing molecules. Additionally, monitoring inorganic chlorine, including chloride ions present during processing, with SPR enhanced by nanomaterials could further improve sensitivity.

TABLE 5. OVERVIEW OF OPTICAL APPROACHES FOR 3-MCPDE DETECTION, SHOWING THE DETECTION LIMITS

Techniques	Sample	LODs	Reference
UV-Vis spectra of GSH-AuNPs/SPR	3-MCPD	-	Faramitha et al. (2023)
Cysteine-coated silver nanoparticles (AgNPs)/UV-Vis	3-MCPD	2,828 µg/kg	Mahardika et al. (2023)
Optical fluorescence/ pyrocatechol-polyethyleneimine (PCh-PEI)	3-MCPD	0.060 mg/L	Xu et al. (2024)
Optical dosimeter based on a benzothiazole derivative	3-MCPD	0.048 mg/L	Zhao et al. (2025)

Despite these promising advances, several challenges remain. One major issue is developing receptors that are both highly selective and sensitive enough to operate effectively in the complex matrices of edible oils. An equally important technical hurdle is the need for efficient sample extraction and enrichment strategies such as microfluidic pre-treatment, phase separation, or affinity-based extraction to isolate 3-MCPDE or its precursors and effectively present them to the sensor surface. *Table 6* highlights different applications of SPR-based biosensors for monitoring oil contaminants and clinically relevant analytes, with associated sensitivity data.

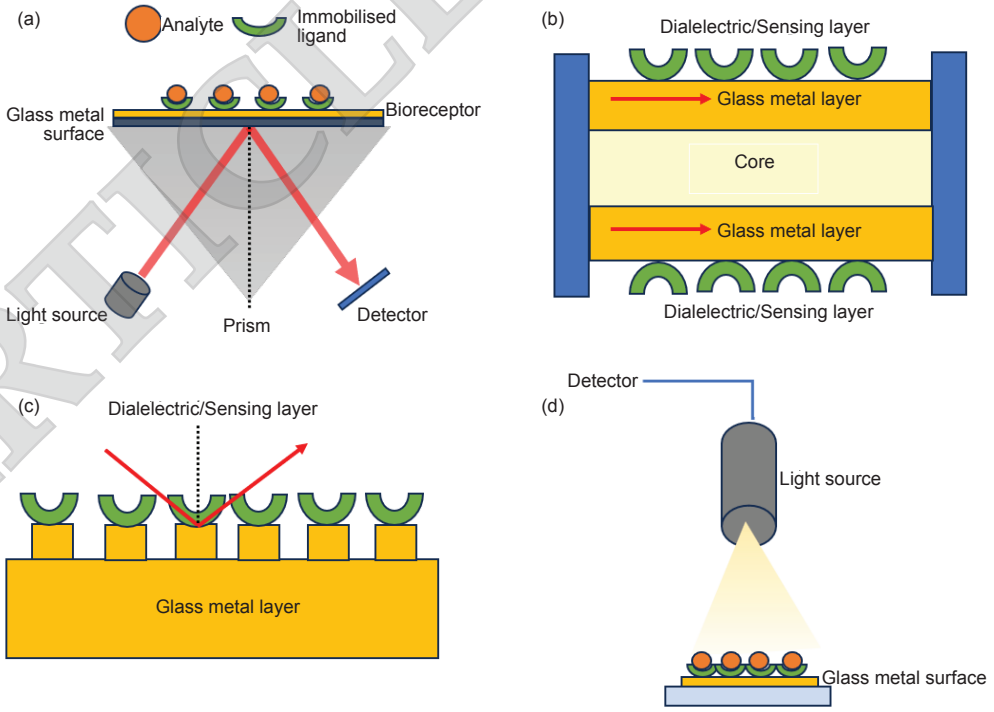
In conclusion, a thorough, in-depth study is essential to address these challenges for SPR-based optical biosensors. Optimising sensor selectivity, refining sample processing techniques and incorporating advanced signal amplification strategies through nanoparticles and carbon dots could lead to a robust, real-time and on-site detection system for 3-MCPDE. Such developments would represent a significant step forward in early-warning systems for the food industry, ultimately reducing consumer exposure to carcinogens and enhancing overall food safety. *Figure 4* provides an overview of the main SPR sensor configurations that have been employed in optical biosensing.

CONCLUSION

In summary, this review highlights that chromatographic techniques such as LC-MS/MS and GC-MS remain the gold standard for detecting 3-MCPDE in edible oils, offering high accuracy but with drawbacks including complex sample preparation, high costs and long analysis

TABLE 6. REPORTED APPLICATIONS OF SPR-BASED BIOSENSORS IN OIL CONTAMINANTS AND HEALTH-RELATED ANALYTES, INCLUDING THEIR SENSITIVITY DATA

Sample	LODs	Reference
Organochlorine (DDT) and chlorpyrifos via water samples	20 ng/L	Mauriz et al. (2006)
Polychlorinated biphenyl (PCB) in aqueous solution	0.1 ppb	Hong et al. (2008)
Organochlorine in oil	0.0153 µg/L	Bakar et al. (2025)
Kidney disease	-	Mulyanti et al. (2022)
Heavy metals	-	Amirjani et al. (2018)



Source: Balbinot et al. (2021).

Figure 4. Schematic illustration of different surface plasmon resonance (SPR) configurations: (a) Prism-based (Kretschmann), (b) optical fibre-based, (c) grating-coupled and (d) localised SPR (LSPR).

times. To complement these methods, emerging approaches such as spectroscopic techniques, electrochemical sensors and SPR-based optical biosensors provide promising alternatives for rapid, real-time and label-free detection. Laboratory studies demonstrate that these innovative strategies can achieve detection limits well below regulatory thresholds, underscoring their potential for routine monitoring. However, challenges remain, particularly regarding sensor stability, reproducibility and performance in complex oil matrices. Moving forward, integrating nanomaterials, improving sample enrichment, and validating these methods in real-world conditions will be critical to advancing them as reliable, on-site screening tools. Ultimately, these complementary approaches can strengthen early-warning systems, enhance food safety and reduce consumer exposure to harmful contaminants.

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