

Activated carbon bleaching for MOAH mitigation in palm oil: a multi-parameter laboratory-scale study using HPLC/GC × GC-FID

Jérôme Grandjean , Aleksandra Gorska , Andrea Pallares Pallares , Antonios Papastergiadis , Sabine Danthine & Giorgia Purcaro

To cite this article: Jérôme Grandjean , Aleksandra Gorska , Andrea Pallares Pallares , Antonios Papastergiadis , Sabine Danthine & Giorgia Purcaro (15 Jul 2026): Activated carbon bleaching for MOAH mitigation in palm oil: a multi-parameter laboratory-scale study using HPLC/GC × GC-FID, Food Additives & Contaminants: Part A, DOI: [10.1080/19440049.2026.2700736](https://doi.org/10.1080/19440049.2026.2700736)

To link to this article: <https://doi.org/10.1080/19440049.2026.2700736>



View supplementary material [↗](#)



Published online: 15 Jul 2026.



Submit your article to this journal [↗](#)



Article views: 145



View related articles [↗](#)



View Crossmark data [↗](#)



Activated carbon bleaching for MOAH mitigation in palm oil: a multi-parameter laboratory-scale study using HPLC/GC×GC-FID

Jérôme Grandjean^{a,b}, Aleksandra Gorska^a, Andrea Pallares Pallares^c, Antonios Papastergiadis^c, Sabine Danthine^b and Giorgia Purcaro^a

^aAnalytical Chemistry Lab, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium; ^bFood Technology, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium; ^cDesmet Innovation Center, Zaventem, Belgium

ABSTRACT

Mineral oil hydrocarbons (MOH) are lipophilic food contaminants that can be present in edible oils. Mineral oil aromatic hydrocarbons (MOAH) are a sub-fraction of MOH and are of particular concern for the European Food Safety Authority (EFSA), as MOAH containing three or more aromatic rings are considered potentially genotoxic. Several studies have shown that certain steps in vegetable oil refining can reduce MOH levels. Deodorisation, in particular, has been reported to significantly decrease overall MOH concentrations. More recently, bleaching with activated carbon (AC) has also been identified as a possible mitigation tool for MOAH. However, no quantitative study has been conducted yet on real edible oil matrices examining the effect of bleaching treatments on MOAH subclasses. The objective of this study was therefore to investigate the effect in spiked palm oil of AC bleaching on the mitigation of MOAH sub-classes (i.e. C-fraction and number of aromatic rings), using HPLC/GC×GC-FID. Two palm oils (preliminary differently treated) were tested with two types of AC. The mitigation effect was evaluated using a Doehlert experimental design combined with response surface methodology, assessing different temperatures (60–80–100 °C) and AC dosages (0.3–0.68–1.05–1.43–1.8%, w/w). Pressure (50 mbar absolute) and contact time (30 min) were kept constant. The results demonstrated that MOAH with three or more aromatic rings can be significantly mitigated by AC bleaching, whereas the adsorption of 1–2 rings MOAH occurred to a much lower extent. In addition to the aromatic ring number, the degree of alkylation influenced adsorption behaviour, with more highly alkylated MOAH showing lower affinity for AC. Among the investigated factors, AC concentration was the most influential parameter: increasing AC dosage led to greater MOAH reduction. Temperature also affected MOAH mitigation in an AC-type-dependent manner. Both AC types resulted in comparable maximal MOAH reductions in both oils, i.e. around 25–30%.

ARTICLE HISTORY

Received 28 April 2026
Revised 29 June 2026
Accepted 1 July 2026

KEYWORDS

Refining; activated carbon; bleaching; adsorption; MOAH; mineral oil; food contaminants; mitigation; palm oil; Doehlert experimental design; response surface methodology; HPLC/GC×GC-FID

Introduction

In recent years, a class of lipophilic food contaminants has become increasingly concerning: mineral oil hydrocarbons (MOH). They are a complex mixture of hydrocarbon compounds containing between 10 and 50 carbon atoms. MOH may be derived from crude oil (petrogenic sources) or synthesised from biomass, coal, and natural gas (EFSA CONTAM, 2012).

From a compositional viewpoint, MOH are usually subdivided into two subgroups: mineral oil saturated hydrocarbons (MOSH) and mineral oil aromatic hydrocarbons (MOAH) (EFSA CONTAM,

2023). MOSH include naphthenes (i.e. alkylated cycloalkanes) and paraffins (i.e. open, linear and branched alkanes), while MOAH are composed of alkylated hydrocarbons containing at least one aromatic ring (EFSA CONTAM, 2012). The latter fraction is considered of great concern for human health because of its potential mutagenic and carcinogenic properties, particularly linked to the presence of polycyclic aromatic compounds (PACs) with three to seven rings and low or no alkylation (Hochegger et al. 2021; Carrillo et al. 2022, 2019). In contrast, no major health risks have been identified for MOSH at current exposure levels, although they are known to accumulate in human tissues (EFSA CONTAM, 2023).

The major sources of contamination in food include environmental contamination, food contact materials, agricultural practices and machinery, ingredients, and processing aids such as lubricating oils for machinery (Hochegger et al. 2021; Purcaro et al. 2016; Brühl 2016). Nevertheless, MOH can also be intentionally added, for instance, in cases of adulteration, or certain food-grade MOH (without MOAH) can be used as food additives (e.g. microcrystalline wax (E905)) or processing aids (Hochegger et al. 2021).

Since the presence of MOAH in food poses a potential risk to consumers (EFSA CONTAM, 2023), several initiatives have been launched to establish control measures for MOH levels in food. In 2022, the *Standing Committee on Plants, Animals, Food and Feed* (SCoPAFF) issued a draft statement proposing limits for total MOAH according to the fat content of the product, with a maximal limit for vegetable fats and oils of 2 mg/kg (European Commission 2022). Although no legislation is currently in force, a vote on maximum MOAH levels and indicative MOSH levels in foodstuffs in the European Union was planned for the end of 2025, with the regulation expected in 2026 and implementation in 2027.

In this context of both consumer risk and emerging legislation, it is relevant to investigate strategies that can help prevent (e.g. through GMP) or reduce MOH contamination, particularly that of MOAH. In edible oils and fats industry, refining plays a crucial role to meet quality and safety requirements through a sequence of operations including degumming, neutralisation, bleaching, dewaxing, and deodorisation. This series of steps removes natural compounds (e.g. free fatty acids, phospholipids, waxes, etc.) that can negatively affect oil stability, shelf life, and final product quality (Gharby 2022). In addition, it may reduce or eliminate chemical contaminants present in the oil (e.g. organic solvents, pesticides, polycyclic aromatic hydrocarbons (PAHs), heavy metals, etc.) (Gharby 2022). Several studies have shown that refining edible oils can reduce MOH content through deodorisation (Wagner et al. 2001; Stauff et al. 2020; Gorska et al. 2024; Ursol et al. 2025), bleaching (Ursol et al. 2025; Moret et al. 2025), and the combination of both (Bauwens et al. 2023).

While the potential of deodorisation for MOH mitigation has been investigated for some time, that of bleaching (*i.e.* an adsorptive treatment notably used to remove pigments, peroxides, salts and/or soaps [Gharby 2022]) has only recently attracted attention. Although MOSH are not known to be significantly reduced by this step (Wagner et al. 2001; Moret et al. 2025), MOAH may be more prone to adsorption due to their structural similarity to polycyclic aromatic hydrocarbons (PAHs), which are known to be removed by certain types of AC (Bauwens et al. 2023; Gibon et al. 2022; Kiralan et al. 2019; Gong et al. 2007). This adsorption behaviour is primarily attributed to π - π dispersive interactions between the aromatic rings of PAHs and the defective graphene layers of AC, possibly reinforced by electron donor-acceptor interactions with surface carbonyl groups (Jian et al. 2017; Pérez and Martín 2015; Marsh and Rodríguez-Reinoso 2006; Xiao et al. 2015; Bu et al. 2011; Dowaidar et al. 2007; Alvarez et al. 2005; Franz et al. 2000). Given the structural analogy between MOAH and PAHs, such mechanisms likely explain the potential of bleaching (particularly when AC is used) to promote partial MOAH removal. This hypothesis is supported by recent experimental data, notably the studies conducted in 2025 by Ursol et al. (2025) and Moret et al. (2025). The former quantitatively investigated MOAH contents in olive pomace oils at different refining stages (crude, after neutralisation, after bleaching, and after deodorisation) by on-line hyphenated high performance liquid chromatography-gas chromatography with flame ionisation detection (HPLC-GC-FID), and complemented this with a qualitative assessment of MOAH profiles before and after bleaching with AC by comprehensive bidimensional gas chromatography coupled to time-of-flight mass spectrometric detection (GC $\times$ GC-TOFMS). A decrease in alkylated and non-alkylated 2-4-ring polycyclic aromatic compounds (PACs) was observed; however, firm conclusions could not be drawn because the samples underwent epoxidation prior to analysis (*i.e.* a purification step intended to remove interfering olefins from the MOAH fraction but known to cause partial PAC removal (Bauwens et al. 2023; Biedermann et al. 2020)).

In the second study, Moret et al. (2025) compared five adsorbents for their ability to mitigate MOH and selected PACs in *n*-hexane, used as a model system in place of real oil. Of the five adsorbent materials tested, AC was the most effective. MOAH and MOSH contents were reduced by approximately 40% and 10%, respectively. A competitive adsorption effect between MOAH and heavier PAHs was also reported. Although these findings are promising, the study was conducted in *n*-hexane rather than in oil, which simplified analysis by avoiding matrix interferences (e.g. olefins) but did not account for potential matrix effects from oil components.

The objective of this study was therefore to investigate the mitigation of MOAH, particularly MOAH ≥ 3 rings, by bleaching with AC in real conditions, *i.e.* using two types of palm oil to simulate different levels of naturally occurring interferences. The effect of different bleaching parameters was investigated using a Doehlert experimental design. All analyses were performed using a validated HPLC/GC $\times$ GC-FID instrument (Bauwens, Barp, et al. 2023) to provide detailed characterisation of the full classes impacted by the process.

Materials and methods

Standards, solvents, and reagents

The MOSH/MOAH internal standard (IS, Restek #31070) and retention time (RT) standard (Restek #31076) were kindly supplied by Restek (Neukirchen-Vlun, Germany). The IS consists of 0.3 mg/mL *n*-undecane (C11), 0.15 mg/mL *n*-tridecane (C13), 0.3 mg/mL bicyclohexyl (CyCy), 0.6 mg/mL cholestane (5- α -cholestane, Cho), 0.3 mg/mL 1-methylnaphthalene (1MN), 0.3 mg/mL 2-methylnaphthalene (2MN), 0.3 mg/mL *n*-pentylbenzene (5B), 0.6 mg/mL perylene (Per), and 0.3 mg/mL 1,3,5-tri-*t*-butylbenzene (TBB) in toluene. The RT includes the alkanes *n*-C10, *n*-C13, *n*-C20, *n*-C24, *n*-C25, *n*-C35, *n*-C40, and *n*-C50 at 100 μ g/mL in cyclohexane. The standard elements (P, Ca, Fe, Mg, Na, K, Zn, and Si) in oil solution for Inductively Coupled Plasma – Optical Emission Spectrophotometer (ICP-OES) analyses came from Chem-Lab NV

(Zedelgem, Belgium). They contained 1000 μ g/g of each element.

n-Hexane and acetone (for HPLC) used for chromatographic analyses were supplied by Biosolve (Dieuze, France). *n*-Hexane was redistilled prior to analysis to increase its purity. Dichloromethane LiChrosolv[®] (for HPLC) was obtained from Merck (Darmstadt, Germany). 2-Propanol (for HPLC) was purchased from J.T. Baker[™] (Phillipsburg, New Jersey, USA). V-Solv[™] ICP Solvent for ICP was supplied by VHG Labs Inc. (Manchester, New Hampshire, USA). 2,2,4-Trimethylpentane for spectroscopy was sourced from Thermo Scientific[™] (Waltham, Massachusetts, USA).

Phenolphthalein was purchased from UCB Pharma (Leuven, Belgium). NaOH was supplied by Merck KGaA (Darmstadt, Germany). Standard matrix oil 75 cSt for ICP spectroscopy was obtained from Chem-Lab NV (Zedelgem, Belgium). Sternal motor oil (48%w MOAH) was from a private home. The bleached palm oil (BPO), the refined, bleached and deodorised palm oil (RBDPO), and the two AC (named AC-A & AC-B for confidentiality reasons) were provided by Desmet (Zaventem, Belgium). The Brunauer-Emmett-Teller (BET) surface area, total pore volume, and micropore area of the two AC were determined by an external laboratory.

Prior to any use, all glassware was cleaned with soap, water, distilled water, acetone, and *n*-hexane.

Spiking of the feedstocks

The two feedstocks (BPO and RBDPO) were spiked with Sternal motor oil (SMO) at a concentration of 50 mg/kg. For this purpose, the two feedstocks and the SMO were precisely weighed. BPO and RBDPO barrels were heated at 70 °C for 24 h to fully melt the oils, which were agitated with a pilot-scale spiral blade shaker before, during, and after SMO addition. The beakers containing SMO were rinsed several times with the corresponding palm oil to ensure quantitative transfer. After spiking and homogenisation, three vials of each feedstock were collected as reference samples (*i.e.* MOAH concentration before AC bleaching). The remaining spiked oils were

transferred to aluminium tanks. Feedstocks and samples were stored at 4°C.

Activated carbon bleaching

Experimental design

A Doehlert experimental design (DD) (Cerqueira et al. 2021) was used to study the effects of bleaching temperature (60°C, 80°C, and 100°C) and AC concentration (0.30%, 0.68%, 1.05%, 1.43%, and 1.80%) on MOAH reduction. Pressure and bleaching time were fixed at 50 mbar absolute and 30 min, respectively. The design included seven experimental points and a total of 15 tests when replicates were considered. The DD central point test (80°C-1.05% AC) was repeated three times ($n=3$). The peripheral points were repeated twice ($n=2$): 60°C-0.68% AC, 60°C-1.43% AC, 80°C-0.30% AC, 80°C-1.80% AC, 100°C-0.68% AC, and 100°C-1.43% AC. The experimental matrix is presented in the [supplementary material, Figure S1](#). Two feedstocks and two AC were tested, resulting in $15 \times 2 \times 2$ bleaching experiments in total. The DD, combined with response surface methodology (RSM), enabled efficient data collection and modelling of the effects of the studied parameters (Cerqueira et al. 2021).

Bleaching procedure

The bleaching was performed at laboratory scale. For each experiment, 300 g of melted spiked oil (~70°C) were weighed into a 1 L pear shape flask and heated, in an oil bath (Heating Bath B-300, BÜCHI Labortechnik AG, Flawil, Switzerland), to the tested bleaching temperature (*i.e.* 60, 80, or 100°C). Then, AC was precisely weighed (Mettler Toledo ME204 analytical balance, Greifensee, Switzerland) and added to the oil. The flask containing the mixture (oil+AC) was installed on a rotary evaporator (R-300, BÜCHI Labortechnik AG, Flawil, Switzerland) and heated at the tested temperature for 10 min at atmospheric pressure. Following this pre-bleaching step, the pressure was set at 50 mbar (Vacuum controller (VC Pro 601), Welch Vacuum Technology, Niles, IL, USA) for 30 min and the tested temperature (60, 80, or 100°C) was applied. The flask was rotated at

150 rpm during the entire procedure. After 30 min, vacuum filtration of the oil was carried out using two Whatman® 1 filters stacked on top of each other (11 µm particle retention) placed on a Büchner funnel preheated to 110°C to facilitate filtration. Following, 3 vials of 20 mL were filled with bleached and filtered oil to quantify the remaining MOAH (as described in Section MOH Analysis). The residual oil was stored in a 250 mL flask for analysis of general oil quality parameters (Section Analysis of general oil quality parameters).

Analysis of general oil quality parameters

Analyses of general oil quality parameters were carried out on both feedstocks (BPO and RBDPO) and on a few randomly selected samples after the bleaching tests.

Free fatty acids

Free fatty acids (FFA) were analysed by titration with sodium hydroxide following the AOCS *Ca 5a-40 method*. For palm oil, the free fatty acid content (%FFA, expressed as g/100 g oil) was expressed as palmitic acid equivalent (Japir et al. 2017).

Phosphorus and metal contents

Phosphorus and metal contents were determined using an ICP-OES instrument (iCAP 7000 Series, Thermo Fisher Scientific, Waltham, MA, USA), following the AOCS *Ca 20-99* (phosphorus) and *Ca 17-01* (metals) official methods.

Carotenoids

β-Carotene quantification was carried out by UV spectrophotometry using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan). The oil samples were melted at 50°C, after which 0.1 g of sample was accurately weighed in a 25 mL volumetric flask filled with 2,2,4-trimethylpentane (isooctane). High precision optical cells (10 mm path length) (Hellma Analytics, Müllheim, Germany) were then filled with the samples. Absorbance was measured at 446 nm against a blank containing isooctane. The β-carotene content (mg/kg) was calculated according to Eq. (1),

where A is the absorbance of the sample at 446 nm and m is the mass of the sample (g).

$$\beta\text{-carotene} = \frac{A \times 25 \times 383}{100 \times m} \quad (1)$$

MOH analysis

Sample preparation

A 5-fold diluted solution of MOSH/MOAH IS (Restek #31070) was prepared in *n*-hexane. This solution was kept in the freezer between analyses.

In an HPLC vial, 200.0 ± 5.0 mg of melted oil were accurately weighed. Subsequently, 10 μ L of IS was added, followed by 1000 μ L of distilled *n*-hexane. The vials were sealed with ND9 ZeroSept® PTFE mono screw caps (LABC-Labortechnik, Bovenden, Germany), which contain no polysiloxanes, to prevent interferences in MOH analysis. After vortex homogenisation, the vials were placed in the autosampler of the off-line HPLC/GC $\times$ GC-FID/TOFMS system (Section HPLC/GC $\times$ GC-FID(/TOFMS)) for MOSH/MOAH fractionation. The injection volume was 90 μ L, corresponding to a transfer of less than 20 mg of oil onto the column, which is within the maximal load capacity of the silica column to retain fat (Biedermann et al. 2009). After fractionation and collection of the MOAH fraction, the latter was concentrated to approximately 150 μ L under nitrogen flow and subjected to a second HPLC purification step (injection volume: 100 μ L) for removing carotenes (both subsequent HPLC conditions are explained in Section HPLC/GC $\times$ GC-FID(/TOFMS)) (Gorska et al. 2025). Finally, after concentrating the purified extract to about 150 μ L, it was injected (90 μ L) for GC $\times$ GC-FID analysis (Section HPLC/GC $\times$ GC-FID(/TOFMS)). All samples were subjected to the same analytical workflow.

HPLC/GC $\times$ GC-FID(/TOFMS)

The analyses were performed on an off-line HPLC/GC $\times$ GC-FID/TOFMS system with a PAL3 Autosampler (PAL System from CTC, Switzerland).

The HPLC part consisted of an Agilent 1260 Infinity II HPLC, a binary pump (G7112B), and a variable wavelength detector (G7114A) acquiring at 230 nm (Agilent Technologies, Waldbronn, Germany).

Elution was performed on an Allure silica column from Restek (250 mm $\times$ 2.1 mm i.d. $\times$ 5 μ m dp, with a pore size of 60 Å) using a gradient of distilled *n*-hexane (C6) and dichloromethane (DCM).

For MOSH/MOAH fractionation, the LC gradient was programmed as follows: 0.0–1.5 min, 100% C6 at 300 μ L/min; 1.5–6.0 min, 65% C6 and 35% DCM at 300 μ L/min. The backflush in reverse mode was performed from 6.1 to 15.0 min with 100% DCM at 500 μ L/min. Reconditioning in forward mode was then carried out from 15.1 to 25.1 min with 100% C6 at 500 μ L/min, followed by 25.2–30.0 min at 300 μ L/min. Only the MOAH fraction, eluting between 4.4 and 5.9 min (corresponding to a collected volume of 450 μ L) was transferred into a clean vial using the autosampler's LC collection tool during this interval.

For MOAH LC purification following MOSH/MOAH fractionation, the gradient was adapted from Gorska et al. (2025) and set as follows: 0.0–1.5 min, 100% C6 at 300 μ L/min; 1.5–14.5 min, 98% C6 and 2% DCM at 300 μ L/min; 14.5–23.0 min, 95% C6 and 5% DCM at 300 μ L/min. Backflush in reverse mode: 23.1–32.1 min, 100% DCM at 500 μ L/min. Reconditioning in forward mode: 32.2–42.2 min, 100% C6 at 500 μ L/min; 42.3–47.3 min, 100% C6 at 300 μ L/min. The MOAH fraction was collected between 3.5 and 20.5 min into a single 10 mL vial, yielding a total collected volume of 5400 μ L. Correct collection and recovery of the MOAH fraction were verified based on the recoveries of the five MOAH ISs, with Per marking the end of the fraction.

The GC system consisted of a Pegasus BT 4D GC $\times$ GC TOFMS (LECO, St. Joseph, MI, USA) equipped with an Agilent 8890 gas chromatograph, a quad-jet dual-stage thermal modulator, a secondary oven, an FID, and a TOFMS. For the present work, only flame ionisation detection (FID) was employed. The FID line was fitted with a cold on-column (COC) injector, connected to a retention gap (Restek Guard Column 10 m $\times$ 0.53 mm), which was coupled *via* a T-union to a solvent vapour exit (SVE) and a Rxi-17Sil MS 15 m $\times$ 0.25 mm $\times$ 0.25 μ m column, itself connected to a Rxi-1MS HT 0.8 m $\times$ 0.15 mm $\times$ 0.15 μ m column. All these columns were kindly supplied by Restek (Neukirchen-Vlun, Germany).

The carrier gas was helium, maintained at a constant flow of 2 mL/min. Injection was performed in large-volume mode (90 μ L) at 59°C, with the SVE kept open for 0.6 min post-injection. The main oven temperature program was as follows: 59°C for 5 min, then increased to 350°C at 5°C/min. Maximum temperature was maintained for 5 min. The secondary oven and the modulator followed the same program, with offsets of +5°C and +15°C, respectively. Modulation took place every 6 s.

The FID parameters were as follows: hydrogen and air flow were equal to 40 mL/min and 400 mL/min, respectively; make-up gas flow (helium) was maintained at 30 mL/min; and detector temperature was 370°C.

Data acquisition, integration, and expression of results

Data acquisition and integration were performed with ChromaTOF Version 5, with the MOSH/MOAH extension.

MOAH were integrated according to their carbon number (C16-C20; C20-C25; C25-C35; C35-C40) and number of aromatic rings (1–2 rings; ≥ 3 rings), after blank subtraction and interference trimming following the procedure described by Bauwens et al. (2021). The integration mask used for quantifying the different MOAH subclasses is provided in the [supplementary material, Figure S2](#). The IS peak areas and ratios were controlled in all samples. Quantification was performed using 1MN, except in cases of impurity co-elution, where 2MN was used instead.

Removal percentages were calculated from the initial spiked MOAH concentrations remeasured within each analytical batch, thereby reducing variability associated with inter-batch instrumental variation. For comparability in reporting absolute removals, results were subsequently normalised to a nominal initial MOAH content of 25.0 mg/kg, and absolute removals for each sub-fraction were expressed relative to this reference value.

Limits of detection (LOD) and quantification (LOQ)

The determination of the method's LOD and LOQ was made based on the recommendations of the

Joint Research Center's (JRC) guidance for MOSH/MOAH analysis (European Commission. Joint Research Centre 2023) and the JRC 'Guidance Document on the Estimation of LOD and LOQ for Measurements in the Field of Contaminants in Feed and Food' (European Commission. Joint Research Centre 2016). Briefly, samples of each unspiked oil (BPO and RBDPO) were analysed following the workflow described in section Sample preparation. They were then integrated following the procedure described in section Data acquisition, integration, and expression of results, and the LOD was obtained by calculating the standard deviation of each sub-area, multiplied by 3.9 (statistical factor as described in [European Commission. Joint Research Centre 2016]). The LOQ was calculated as 3.3 times the LOD.

Data elaboration: Response surface methodology

Response Surface Methodology (RSM) was applied to model MOAH removal (%) as a function of bleaching temperature and AC concentration. Four model structures were evaluated in RStudio (version 2023.09.0, Build 463) using the *rsm* package: a first-order model $[FO(x_1, x_2)]$, a first-order model including the two-way interaction term $[FO(x_1, x_2) + TWI(x_1, x_2)]$, a full second-order model $[FO(x_1, x_2) + TWI(x_1, x_2) + PQ(x_1, x_2)]$, and a second-order model without the interaction term $[FO(x_1, x_2) + PQ(x_1, x_2)]$. Model selection was based on the adjusted R^2 , the significance of the overall model ($p < 0.05$), the number of significant coefficients ($p < 0.05$), and a non-significant lack-of-fit test ($p > 0.05$). Model parsimony was also considered, and non-significant terms were not retained when they increased complexity without improving explanatory quality.

Results and discussion

This study aimed to investigate the reduction of MOAH during the bleaching of palm oil with AC. Two oils, BPO and RBDPO, were selected based on their differences in β -carotene and free fatty acid (FFA) contents to assess their potential for competing with MOAH during adsorption. The composition of the selected oils (phosphorus, metals, FFA, β -carotene) is presented in

Table S1 (supplementary material): as expected based on the processing steps applied, RBDPO contained less FFA and β -carotene than BPO, while the metal and phosphorus contents were similar.

Regarding the two AC used, the textural properties (**Table 1**) showed that AC-A had a higher BET surface area (+6.97%) and pore volume (+11.7%) than AC-B, while AC-B had a higher micropore area (+5.14%).

A Doehlert design was used to perform a first exploratory study on the impact of bleaching conditions on MOAH removal. Temperatures of 60°C, 80°C, and 100°C (the latter being the usual temperature for bleaching (Gharby 2022; Bauwens et al. 2023; Kiralan et al. 2019; Aliyar-Zanjani et al. 2019)) were tested. Concentrations of AC ranging from 0.3 to 1.8% (w/w) were studied, with 0.3% being the usual concentration used in industry for removal of PAHs (Bauwens et al. 2023; Kiralan et al. 2019; Aliyar-Zanjani et al. 2019). Higher-than-usual AC concentrations were tested to explore the full potential of the adsorbent for MOAH removal. The bleaching procedures were performed under vacuum (50 mbar) for 30 min, which are usual treatment conditions (Gharby 2022; Usman et al. 2012).

The LODs and LOQs of the method used for quantifying MOAH according to carbon number range and number of aromatic rings are presented in **Table 2** for the two oils used in the bleaching

tests (*i.e.* BPO and RBDPO). As shown, the LOQs for total MOAH are higher than those specified in ISO 20122:2024 for vegetable oils (ISO 2024 and in the JRC guidance for MOSH/MOAH analysis (European Commission 2022) (*i.e.* 2 mg/kg) as no sample enrichment step (saponification) was performed. This step was intentionally omitted to simplify the analytical workflow and minimise additional variability associated with sample preparation. Despite the resulting higher LOQs, all oils were spiked at approximately 25 mg/kg MOAH, and the achieved sensitivity was therefore sufficient for the comparative evaluation of MOAH concentrations before and after bleaching. The observed differences in LOD and LOQ are attributed to procedural blank variability and minor baseline fluctuations in the MOAH region, rather than to a true difference in method sensitivity.

Effect of AC bleaching on MOAH

The MOAH profile of the spiked oils was characterised before the bleaching tests according to carbon number range and number of aromatic rings. These values are shown in **Figure 1**, expressed as percentage of total MOAH profile (the absolute MOAH concentration prior to AC bleaching for each subclass is shown in **Table S2, Supplementary Material**). It is clear that the C20–C35 range exhibited the highest MOAH concentrations, while species with three or more aromatic rings represented roughly 30% of the total MOAH.

For illustration purposes of the qualitative evaluations performed, GC×GC-FID chromatograms of the MOAH fraction before and after bleaching, together with their difference plots, are shown in **Figure 2**. To obtain the **Figure 2 A3**

Table 1. BET surface area, total volume in pores, and micropore area of the two AC.

	AC-A	AC-B
BET Surface Area (m ² /g)	1076	1001
Micropore Area (m ² /g)	204.7	215.8
Total Volume in Pores (cm ³ /g)	0.7268	0.6417

Table 2. Limits of detection (LOD) and limits of quantification (LOQ), both expressed in mg/kg, for each MOAH sub-fraction and each tested oil. BPO: bleached palm oil; RBDPO: bleached and deodorised palm oil.

MOAH sub-fraction		LOD		LOQ	
		BPO	RBDPO	BPO	RBDPO
C16–C20	1–2 rings	0.33	0.41	1.10	1.3
	≥3 rings	0.07	0.05	0.22	0.15
C20–C25	1–2 rings	0.67	0.71	2.2	2.4
	≥3 rings	0.18	0.16	0.59	0.51
C25–C35	1–2 rings	1.4	0.74	4.6	2.5
	≥3 rings	0.54	0.51	1.8	1.7
C35–C40	1–2 rings	0.76	0.17	2.5	0.55
	≥3 rings	0.32	0.18	1.1	0.61
Total MOAH		3.6	2.8	11	9.2

and B3 the subtraction feature of the GC×GC software was used by subtracting the A2 (B2) from the A1 (B1) chromatogram. Only the results obtained at one temperature are displayed, since chromatograms at other temperatures exhibited the same qualitative behaviour. For each oil under evaluation, the effect of different AC

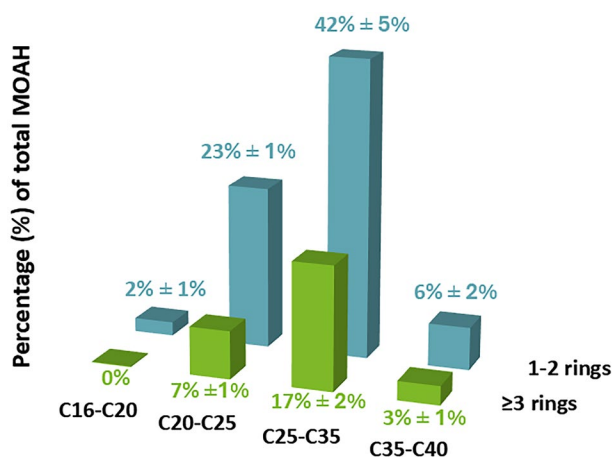


Figure 1. Average initial MOAH composition after oil spiking, with MOAH content in each sub-fraction expressed as a percentage of total MOAH.

concentrations is illustrated. Two main features emerged: (i) the fractions containing ≥ 3 aromatic rings were the most strongly reduced, and (ii) increasing the AC concentration led to progressively greater MOAH removal.

Removal of total MOAH

Following the qualitative evaluation of MOAH removal after bleaching, a quantitative analysis was performed. Hence, the total amount of MOAH removed as a function of bleaching temperature and AC concentration is shown in Figure 3 for both oils. Figure 3(a) and (b) report the results for RBDPO, whereas Figure 3(c) and (d) present the corresponding data for BPO. These measurements were obtained using a Doehlert experimental design (Cerqueira et al. 2021), enabling the systematic evaluation of factor interactions and supporting the subsequent construction of response surfaces (see Section Removal of total MOAH).

The first and most evident trend is that increasing the amount of AC used during bleaching led to greater MOAH reduction (aligning with the

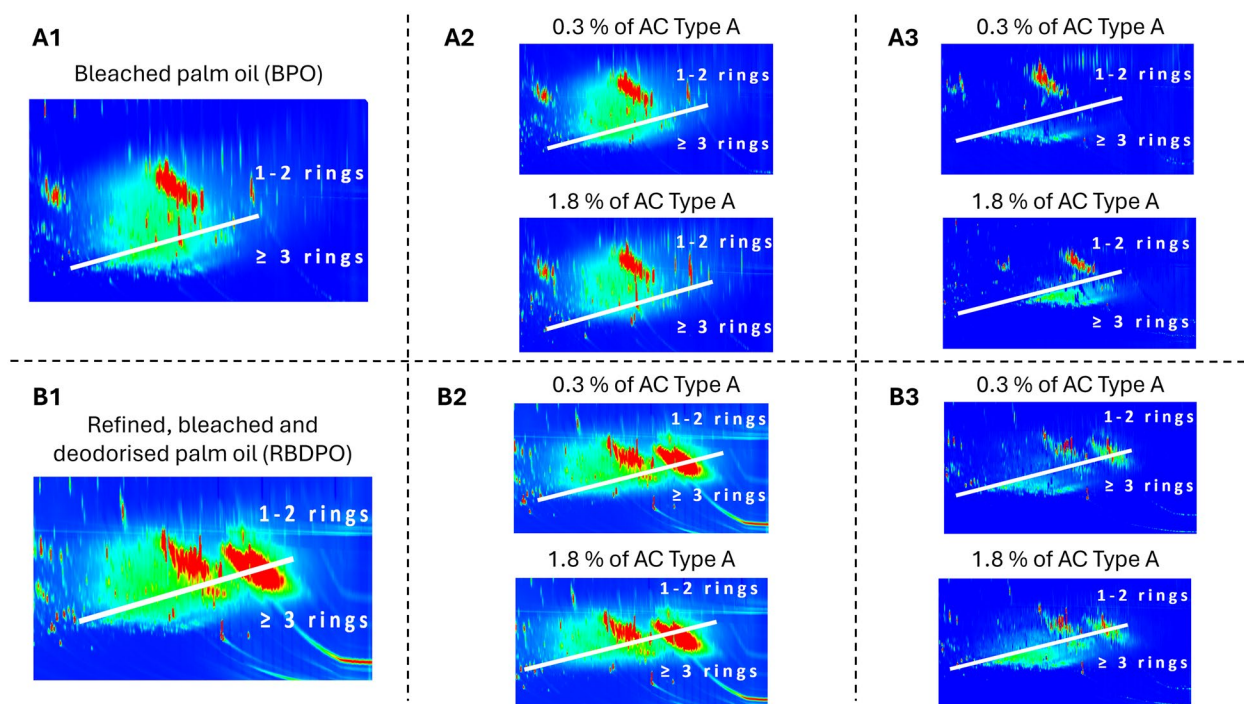


Figure 2. GC×GC-FID chromatograms of bleached palm oil (A1, A2, A3) and bleached and deodorised palm oil (B1, B2, B3) before bleaching (A1 and B1), after bleaching (A2 and B2) and the difference between before and after bleaching (A3 and B3) obtained by using the subtraction feature of the ChromaTOF software for MOSH/MOAH (LECO). The subtraction chromatograms are intended for qualitative visualisation only, as no normalisation was performed to account for small differences in sample concentration between analyses. The conditions tested were as follows: temperature = 80 °C, time = 30 min, pressure = 50 mbar and stirring speed = 150 rpm. The percentage of activated carbon used during bleaching is noted above each chromatogram.

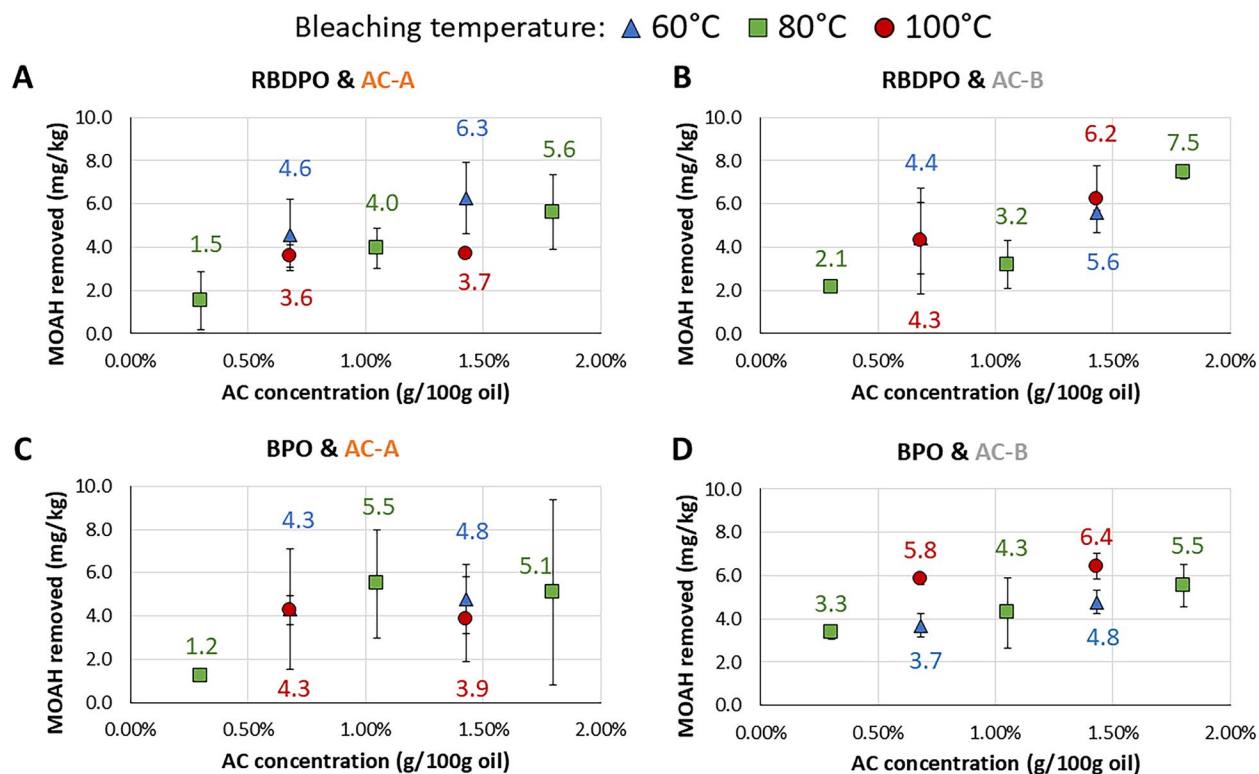


Figure 3. Total MOAH removal (mg/kg) as a function of AC percentage (g/100 g oil) used and bleaching temperature for AC-A and RBDPO (a), AC-B and RBDPO (b), AC-A and BPO (c) and AC-B and BPO (d). The points on the graphs are means of three replicates ($n=3$) for the central points (80°C - 1.05% AC) and two replicates ($n=2$) for the other points. The error bars correspond to the standard deviations of the replicates for each point.

findings of Moret et al. (2025) in *n*-hexane solution), irrespective of temperature, AC type, or oil type. The highest observed decrease was 7.5 mg/kg for BPDO at 1.80% AC-B and 80°C, while reductions of more than 4 mg/kg were already achieved at approximately 0.7% AC, regardless of AC type or oil type.

Regarding the effect of temperature, it appears that AC-A and AC-B exhibit opposite behaviours: for AC-A, increasing the temperature led to a decrease in MOAH removal, whereas for AC-B, an increase was observed. A tentative explanation for this phenomenon is provided above.

Overall, it was not possible to conclude that one AC is significantly more efficient than the other for MOAH removal, given that their impacts on this process depend on the temperature applied.

Finally, the type of feedstock does not appear to exert a major influence on the mitigation, or at least the variability within the dataset prevents establishing a clear differentiation between feedstocks.

Removal of MOAH Sub-fractions

Given that qualitative evaluations (Figure 2) indicated that MOAH were removed to different extents depending on their chemical structure, a quantitative evaluation of MOAH removals by sub-fraction was performed, and the results are presented in Figure 4. The percentages of MOAH removed were evaluated as a function of temperature and AC dosage. The C16–C20 1–2-rings and ≥ 3 -rings classes were excluded because their initial absolute MOAH levels were extremely low (Figure 1). To avoid distorting the graphical representation, these classes were omitted, while the complete dataset is provided in the [supplementary material, Table S3.A and Table S3.B](#).

From Figure 4, it stands out that MOAH with ≥ 3 rings exhibited the highest reduction, underscoring their affinity for AC. This behaviour is consistent with what is already known for PAHs (Marsh and Rodríguez-Reinoso 2006; Xiao et al. 2015; Bu et al. 2011; Dowaidar et al. 2007; Alvarez et al. 2005). MOAH share the same aromatic ring structures as PAHs, differing mainly by their

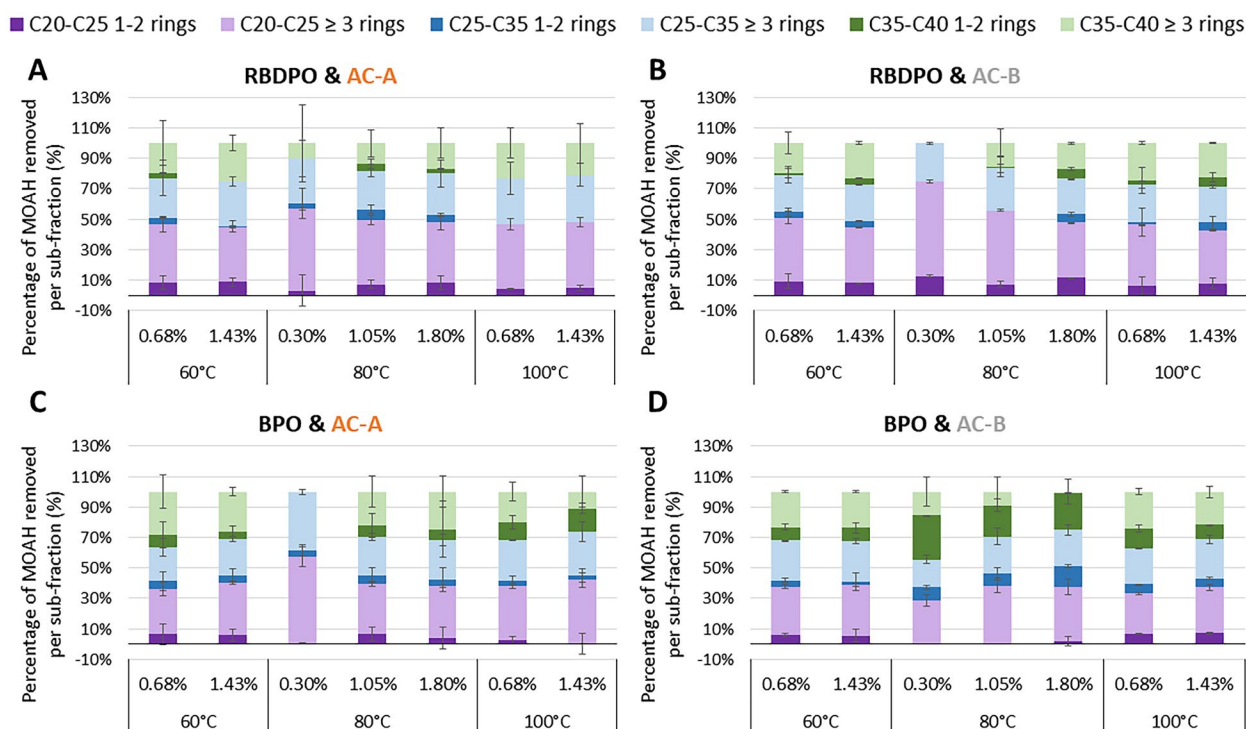


Figure 4. Percentage (%) of MOAH removed, by subfractions, as a function of temperature and AC concentration for RBDPO and AC-A (a), RBDPO and AC-B (b), BPO and AC-A (c), and BPO and AC-B (d).

alkylation; it is therefore reasonable to hypothesise that π - π dispersive interactions also occur between MOAH and AC.

Another effect visible in Figure 4 is that the percentage mitigation of MOAH ≥ 3 rings decreased as the carbon number increased: C20-C25 ≥ 3 rings were removed more efficiently than C25-C35 ≥ 3 rings, which in turn showed greater reduction than C35-C40 ≥ 3 rings. A plausible explanation lies in the distribution of weakly versus strongly alkylated MOAH within these sub-fractions, which is determined by the original composition of the mineral oil. Qualitative inspection of the GC $\times$ GC chromatogram of the MOAH source, interpreted following the guidance in (EURL-PC 2025), indicates that the proportion of weakly alkylated MOAH decreases with increasing carbon number intervals (*i.e.* there are more highly branched MOAH in the C25-C35 fraction than there are in the C20-C35 one). Strongly alkylated structures introduce steric hindrance that limits their adsorption on the active sites of AC – an effect already reported (Moret et al. 2025). Consequently, the C20-C25 ≥ 3 -ring class is more efficiently adsorbed, as it contains fewer strongly alkylated species,

whereas the C25-C35 and C35-C40 ≥ 3 -ring classes exhibit lower absolute removals.

Response surfaces per Sub-fraction

As previously mentioned, the bleaching experiments were conducted using a Doehlert experimental design to model the response surface of MOAH removal as a function of AC concentration and bleaching temperature. This approach provides a clearer understanding of how these parameters influence the mitigation. Because MOAH ≥ 3 rings showed the strongest response to bleaching, the modelling was restricted to this class. Figure 5 presents the RSM models for the C20-C25 ≥ 3 -ring and C25-C35 ≥ 3 -ring classes. The C35-C40 ≥ 3 -ring models are not shown because some of them were not statistically significant and/or exhibited negative R^2 values, likely due to the low initial concentration of this sub-fraction (Figure 1).

The response surfaces show differences between the considered C-fractions and between the AC types. Since the quantitative discussion has already been presented, the discussion here

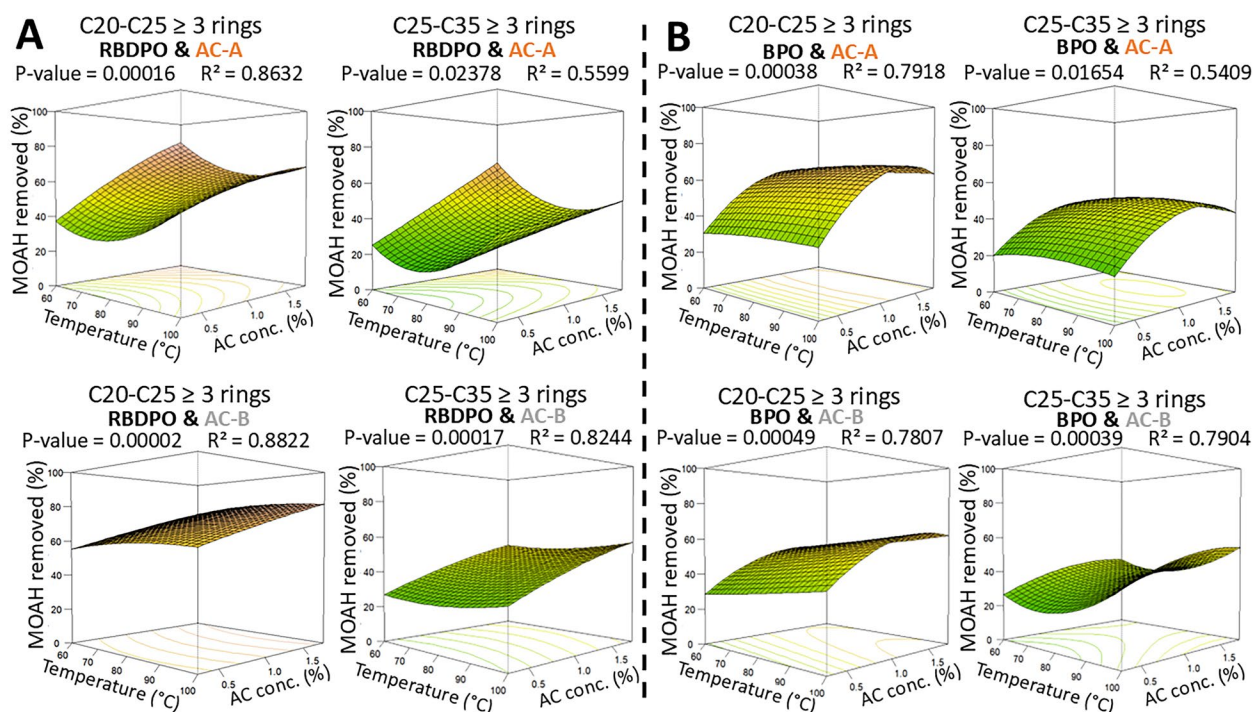


Figure 5. Response surface plots of MOAH removal (%) for the C20–C25 ≥ 3-ring and C25–C35 ≥ 3-ring sub-fractions as a function of AC concentration (% w/w) and temperature (°C) for (A) bleached and deodorised palm oil and (B) bleached palm oil.

focuses on the relative influence of the experimental factors.

For both oils, activated carbon concentration was the dominant factor governing MOAH reduction (p -values ≤ 0.0064). Increasing the AC dose consistently enhanced the removal of ≥ 3 -ring MOAH, but the dose–response was not linear. The significant quadratic term associated with AC, together with the response surfaces, indicates that the increase in removal efficiency gradually diminishes as the AC concentration increases (*i.e.* the slope of the ‘MOAH removed’ curve decreases as AC concentration increases) – a behaviour consistent with the adsorption characteristics reported by Moret et al. (2025). The models indicate a steep improvement up to roughly 0.7–0.9% AC, followed by a marked decrease in slope beyond 1%, where additional AC produces only limited incremental gains. Given this diminishing-return profile, an operating point of around 0.8% AC is technically effective. The conventional industrial dosage for PAH removal is generally $\sim 0.3\%$.

Temperature is also a significant factor for some models ($0.0142 \leq p$ -values ≤ 0.9161), though less influential than AC concentration. As

discussed in Section Removal of total MOAH, its effect depends on the AC type, and the interaction with AC dose is non-significant in all models, indicating independent contributions. AC-A achieves its highest mitigation of ≥ 3 -ring MOAH at temperatures below 80°C , whereas AC-B shows improved performance at higher temperatures.

A plausible explanation is partial MOAH desorption from AC-A at temperatures above $\sim 80^\circ\text{C}$. Torrents et al. (1997) showed that aromatic compounds can desorb from AC at relatively low temperatures. Carratalá-Abril et al. (2010) reported earlier desorption for carbons with larger mesopore volume and broader pore-size distributions; and Veksha et al. (2012) demonstrated that desorption temperatures vary with AC porosity, surface chemistry, and humidity, and may begin below 100°C under dry conditions. Because AC-A has a higher total pore volume (+12% relative to AC-B; Table 1), diffusion constraints are expected to be lower, which would shift the onset of desorption to lower temperatures. This would explain why AC-A shows optimal performance below 80°C and reduced efficiency above this threshold. For example, in RBDPO at 1.8% AC-A, predicted C20–C25 ≥ 3 -ring

MOAH mitigation decreases from 87.5% at 60°C to 64.0% at 85°C. AC-B, with its smaller pore volume, does not exhibit such behaviour within this temperature range and therefore shows an optimum above 80°C.

In summary, the models show that AC concentration governs the overall efficiency of ≥ 3 -ring MOAH removal, whereas temperature modulates this efficiency in an AC-type-dependent manner. These combined factors account for the distinct response surfaces obtained for the two sorbents and specifically for the shift of the optimum to $< 80^\circ\text{C}$ with AC-A and to higher temperatures with AC-B.

Comparison with previous studies

The only other study in literature that has quantified MOH mitigation during bleaching with AC as adsorbent is Moret et al. (2025). Under their optimal conditions (1.25% AC, 60 min, 30°C; performed in hexane), they reported a total MOAH reduction of approximately 40%.

In the present work, when all oils and AC types were considered together, the mean total MOAH reduction was around 30% (supplementary material, Table S4). Several methodological differences must be considered when assessing the discrepancies between the current study and that of Moret et al.

A first distinction is the matrix: Moret et al. carried out adsorption trials in hexane, whereas the present experiments were performed directly in edible oils, where matrix effects and competitive adsorption reduce apparent mitigation. The AC concentrations were similar across the studies, but other conditions differed markedly. Moret et al. used a 60-min contact time, while the present work employed 30 min; it must be however stated that they observed no significant time effect, which is consistent with the rapid equilibrium typically reached in bleaching processes (~ 15 min) (Rich 1967). Furthermore, the temperature used in the work of Moret et al. (30°C) was also far below those used in the current study (60, 80 and 100°C) or those recommended for industrial bleaching (100–120°C) (Gupta 2017); nevertheless, such low temperature still yielded substantial MOAH removal in the model system with hexane.

An additional difference concerns the origin and composition of the MOAH fraction. Moret et al. employed Gravex, a lighter mineral oil fraction expected to contain MOAH with a lower degree of alkyl substitution. Such compounds are less sterically hindered and can more readily access and interact with the activated carbon surface, irrespective of whether they belong to the 1–2 ring or ≥ 3 ring classes.

In contrast, the mineral oil investigated in the present study falls within a slightly heavier boiling range. The MOAH 1–2 ring fraction in this material was predominantly composed of highly alkylated species, which are characterised by increased steric hindrance and reduced accessibility to the carbon surface. This compositional difference may have also contributed to the lower adsorption efficiency observed in the present work and could partly explain the slightly higher MOAH removal reported by Moret et al.

Taken together, these contrasts in matrix, temperature, contact conditions and MOAH composition make direct numerical comparison inappropriate. Nevertheless, the mitigation levels reported in both studies remain within a comparable order of magnitude once the experimental differences are considered.

Conclusions

The present study investigated the effect of AC bleaching on MOAH mitigation in palm oil, with specific emphasis on the influence of AC type (two materials), bleaching temperature, AC concentration, and oil type (bleached versus bleached and deodorised). The combined use of HPLC/GC $\times$ GC-FID and LC-based removal of biogenic interferences (shown to have a minimal impact on MOAH quantification compared to epoxidation-based purification) enabled the assessment of changes in MOAH sub-fractions, with particular focus on compounds containing 1–2 and ≥ 3 aromatic rings.

Across all experimental conditions, MOAH species containing ≥ 3 aromatic rings were removed more efficiently than those containing 1–2 rings. This behaviour is consistent with stronger π – π dispersive interactions between the π -electron systems of higher-ring MOAH and

defective graphene layers in the AC. The extent of removal was additionally influenced by the degree of alkylation: increased alkylation led to enhanced steric hindrance, thereby reducing adsorption onto the AC surface.

Among the bleaching parameters investigated, AC concentration had the strongest impact on MOAH mitigation. Higher AC concentration resulted in increased removal; however, the relationship was non-linear, with diminishing gains in removal efficiency at higher concentrations. An effective operating point of around 0.8% AC was identified, which is higher than the standard industrial dosage for PAH removal (0.3%). Temperature effects were AC-dependent, indicating that the chemical and structural properties of the AC govern the optimal adsorption conditions. For AC-A, MOAH removal efficiency decreased above 80 °C, likely due to partial thermal desorption. In contrast, AC-B exhibited optimal performance at higher temperatures.

Based on the present dataset and associated variability, no statistically supported differences could be established between the two palm oil types, nor between the overall mitigation efficiencies of the two AC. When results were pooled across oil types and AC materials, MOAH mitigation reached approximately 5–8 mg/kg from an initial spiking level of 25 mg/kg.

In conclusion, this exploratory study demonstrated the potential of AC bleaching to mitigate MOAH containing ≥ 3 aromatic rings under industrially relevant conditions, although no clear optimal operating conditions could be identified within the investigated experimental domain.

Acknowledgements

The authors would like to thank LECO and Restek for providing the analytical instruments and equipment used in this study. This work is supported by ACESSE (Academic Center of Excellence for Separation Science and Sensing). This article is based upon work from the Sample Preparation Study Group and Network, supported by the Division of Analytical Chemistry of the European Chemical Society. The authors would also like to thank Kristof Meus and Jeroen Maes for their assistance with the practical execution of the trials at the Desmet Innovation Centre.

Author contributions

CRedit: **Jérôme Grandjean**: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing; **Aleksandra Gorska**: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing; **Andrea Pallares Pallares**: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing; **Antonios Papastergiadis**: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing; **Sabine Danthine**: Conceptualization, Methodology, Supervision, Writing – review & editing; **Giorgia Purcaro**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

- Aliyar-Zanjani N, Piravi-Vanak Z, Ghavami M. 2019. Study on the effect of activated carbon with bleaching earth on the reduction of polycyclic aromatic hydrocarbons (PAHs) in bleached soybean oil. *Grasas Aceites*. 70(2):e304. <https://doi.org/10.3989/gya.0577181>
- Alvarez PM, García-Araya JF, Beltrán FJ, Masa FJ, Medina F. 2005. Ozonation of activated carbons: effect on the adsorption of selected phenolic compounds from aqueous solutions. *J Colloid Interface Sci*. 283(2):503–512. <https://doi.org/10.1016/j.jcis.2004.09.014>
- Bauwens G et al. 2023. Investigation of the effect of refining on the presence of targeted mineral oil aromatic hydrocarbons in coconut oil. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess*. 40(3):392–403. <https://doi.org/10.1080/19440049.2022.2164621>
- Bauwens G, Barp L, Purcaro G. 2023. Validation of the liquid chromatography-comprehensive multidimensional gas chromatography-time-of-flight mass spectrometer/flame ionization detector platform for mineral oil analysis exploiting interlaboratory comparison data. *Green Anal Chem*. 4:100047. <https://doi.org/10.1016/j.greeac.2022.100047>
- Bauwens G, Pantó S, Purcaro G. 2021. Mineral oil saturated and aromatic hydrocarbons quantification: mono- and two-dimensional approaches. *J Chromatogr A*. 1643:462044. <https://doi.org/10.1016/j.chroma.2021.462044>
- Biedermann M, Fiselier K, Grob K. 2009. Aromatic hydrocarbons of mineral oil origin in foods: method for determining the total concentration and first results. *J Agric Food Chem*. 57(19):8711–8721. <https://doi.org/10.1021/jf901375e>

- Biedermann M, Munoz C, Grob K. 2020. Epoxidation for the analysis of the mineral oil aromatic hydrocarbons in food. An update. *J Chromatogr A*. 1624:461236. <https://doi.org/10.1016/j.chroma.2020.461236>
- Brühl L. 2016. Occurrence, determination, and assessment of mineral oils in oilseeds and vegetable oils. *Euro J Lipid Sci Tech*. 118(3):361–372. <https://doi.org/10.1002/ejlt.201400528>
- Bu J et al. 2011. Desulfurization of diesel fuels by selective adsorption on activated carbons: competitive adsorption of polycyclic aromatic sulfur heterocycles and polycyclic aromatic hydrocarbons. *Chem Eng J*. 166(1):207–217. <https://doi.org/10.1016/j.cej.2010.10.063>
- Carratalá-Abril J, Lillo-Ródenas M, Linares-Solano A, Cazorla-Amorós D. 2010. Regeneration of activated carbons saturated with benzene or toluene using an oxygen-containing atmosphere. *Chem Eng Sci*. 65(6):2190–2198. <https://doi.org/10.1016/j.ces.2009.12.017>
- Carrillo J-C et al. 2022. Comparison of PAC and MOAH for understanding the carcinogenic and developmental toxicity potential of mineral oils. *Regul Toxicol Pharmacol*. 132:105193. <https://doi.org/10.1016/j.yrtph.2022.105193>
- Carrillo J-C, Van Der Wiel A, Danneels D, Kral O, Boogaard PJ. 2019. The selective determination of potentially carcinogenic polycyclic aromatic compounds in lubricant base oils by the DMSO extraction method IP346 and its correlation to mouse skin painting carcinogenicity assays. *Regul Toxicol Pharmacol*. 106:316–333. <https://doi.org/10.1016/j.yrtph.2019.05.012>
- Cerqueira UFM et al. 2021. Doehlert design in the optimization of procedures aiming food analysis – a review. *Food Chem*. 364:130429. <https://doi.org/10.1016/j.foodchem.2021.130429>
- Dowaidar AM, El-Shahawi MS, Ashour I. 2007. Adsorption of polycyclic aromatic hydrocarbons onto activated carbon from non-aqueous media: 1. the influence of the organic solvent polarity. *Sep Sci Technol*. 42(16):3609–3622. [etnodéc https://doi.org/10.1080/01496390701626537](https://doi.org/10.1080/01496390701626537)
- European Food Safety Authority Panel on Contaminants in the Food Chain [EFSA CONTAM]. 2012. Scientific opinion on mineral oil hydrocarbons in food. EFS2. 10(6). <https://doi.org/10.2903/j.efsa.2012.2704>
- European Food Safety Authority Panel on Contaminants in the Food Chain [EFSA CONTAM]. 2023. Update of the risk assessment of mineral oil hydrocarbons in food. EFS2. 21(9). <https://doi.org/10.2903/j.efsa.2023.8215>
- European Commission. 2022, 21 avril. Standing committee on plants, animals, food and feed section novel food and toxicological safety of the food chain [SCoPAFF].
- European Commission. Joint Research Centre [JRC]. 2016. Guidance document on the estimation of LOD and LOQ for measurements in the field of contaminants in feed and food. LU: publications Office, Consulté le: 10 août 2025. Online. Disponible sur: <https://data.europa.eu/doi/10.2787/8931>.
- European Commission. Joint Research Centre [JRC]. 2023. Guidance on sampling, analysis and data reporting for the monitoring of mineral oil hydrocarbons in food and food contact materials: in the frame of Commission Recommendation (EU) 2017/84. LU: Publications Office, Consulté le: 4 octobre 2024. Online. Available from: <https://data.europa.eu/doi/10.2760/963728>.
- [EURL-PC] European Union Reference Laboratory for Processing Contaminants. et al. 2025. Analysis of MOSH and MOAH in food by GC×GC: guidance on analysis, interpretation and data reporting. Technical University of Denmark. <https://doi.org/10.11581/FBE4E1CE-65C2-468F-9CEA-CB3A140BEADE>
- Franz M, Arafat HA, Pinto NG. 2000. Effect of chemical surface heterogeneity on the adsorption mechanism of dissolved aromatics on activated carbon. *Carbon N Y*. 38(13):1807–1819. [https://doi.org/10.1016/S0008-6223\(00\)00012-9](https://doi.org/10.1016/S0008-6223(00)00012-9)
- Gharby S. 2022. Refining vegetable oils: chemical and physical refining. *Sci World J*. 2022:1–10. <https://doi.org/10.1155/2022/6627013>
- Gibon V, De Greyt W, Papastergiadis A, Kellens M. 2022. Mineral oil hydrocarbons - a new challenge for the oils and fats processing industry. Accessed March 23, 2025. Available from: https://issuu.com/altitudedesign/docs/1701-a4-mineral_oil_hydrocarbons.
- Gong Z, Alef K, Wilke B-M, Li P. 2007. Activated carbon adsorption of PAHs from vegetable oil used in soil remediation. *J Hazard Mater*. 143(1–2):372–378. <https://doi.org/10.1016/j.jhazmat.2006.09.037>
- Gorska A, Bauwens G, Beccaria M, Purcaro G. 2025. Purification of mineral oil aromatic hydrocarbons and separation based on the number of aromatic rings using a liquid chromatography silica column. An alternative to epoxidation. *J Chromatogr A*. 1743:465684. <https://doi.org/10.1016/j.chroma.2025.465684>
- Gorska A, Danthine S, Jacquet N, Purcaro G. 2024. Impact of deodorisation time and temperature on the removal of different MOAH structures: a lab-scale study on spiked coconut oil. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess*. 41(9):1118–1131. <https://doi.org/10.1080/19440049.2024.2371925>
- Gupta MK. 2017. Bleaching. In *Practical guide to vegetable oil processing*. Elsevier. p. 129–169. <https://doi.org/10.1016/B978-1-63067-050-4.00006-4>
- Hochegger A et al. 2021. Mineral oil risk assessment: knowledge gaps and roadmap. Outcome of a multi-stakeholders workshop. *Trends Food Sci Technol*. 113:151–166. <https://doi.org/10.1016/j.tifs.2021.03.021>
- [ISO] International Organization for Standardization. 2024. ISO 20122:2024—Vegetable oils—Determination of mineral oil saturated hydrocarbons (MOSH) and mineral oil aromatic hydrocarbons (MOAH) with online-coupled high performance liquid chromatography-gas chromatography-flame ionization detection (HPLC-GC-FID) analysis—Method for low limit of quantification. Online. Available from: <https://www.iso.org/standard/86091.html>.
- Japir AA-W et al. 2017. Physicochemical characteristics of high free fatty acid crude palm oil. *OCL*. 24(5):D506. <https://doi.org/10.1051/ocl/2017033>

- Jian MQ, Xie HH, Xia KL, Zhang YY. 2017. Challenge and opportunities of carbon nanotubes. In: *Industrial applications of carbon nanotubes*. Elsevier. p. 433–476. <https://doi.org/10.1016/B978-0-323-41481-4.00015-0>
- Kiralan SS, Toptancı İ, Tekin A. 2019. Further evidence on the removal of polycyclic aromatic hydrocarbons (PAHs) during refining of olive pomace oil. *Euro J Lipid Sci Tech*. 121(4):1800381. <https://doi.org/10.1002/ejlt.201800381>
- Marsh H, Rodríguez-Reinoso F. 2006. *Activated carbon*. 1st ed. Elsevier.
- Moret S, Piazza A, Bouguerra MDE, Barp L. 2025. A preliminary study on the decontamination properties of different sorbent materials used for oil bleaching against mineral oils and selected alkylated polycyclic aromatic hydrocarbons. *OCL*. 32:13. <https://doi.org/10.1051/ocl/2025005>
- Pérez EM, Martín N. 2015. π - π interactions in carbon nanostructures. *Chem Soc Rev*. 44(18):6425–6433. <https://doi.org/10.1039/c5cs00578g>
- Purcaro G, Barp L, Moret S. 2016. Determination of hydrocarbon contamination in foods. A review. *Anal Methods*. 8(29):5755–5772. <https://doi.org/10.1039/C6AY00655H>
- Rich A. 1967. Major factors that influence bleaching performance. *J Am Oil Chem Soc*. 44(7):298A–323A.
- Stauff A, Schnapka J, Heckel F, Matissek R. 2020. Mineral oil hydrocarbons (MOSH/MOAH) in edible oils and possible minimization by deodorization through the example of cocoa butter. *Euro J Lipid Sci Tech*. 122(7):1900383. <https://doi.org/10.1002/ejlt.201900383>
- Torrents A, Damera R, Hao OJ. 1997. Low-temperature thermal desorption of aromatic compounds from activated carbon. *J Hazard Mater*. 54(3):141–153. [https://doi.org/10.1016/S0304-3894\(96\)01878-X](https://doi.org/10.1016/S0304-3894(96)01878-X)
- Ursol LM, Conchione C, Peroni D, Moret S. 2025. A study on the impact of industrial-scale refining on olive oil and olive pomace oil contamination with mineral oils. *Food Chem*. 466:142207. <https://doi.org/10.1016/j.foodchem.2024.142207>
- Usman MA, Ekwueme VI, Alaje TO, Mohammed AO. 2012. Characterization, acid activation, and bleaching performance of Ibeshe Clay, Lagos, Nigeria. *ISRN Ceram*. 2012:1–5. <https://doi.org/10.5402/2012/658508>
- Veksha A, Uddin A, Sasaoka E, Kato Y. 2012. Adsorption and desorption behavior of benzene on activated carbons from different precursors in dry and humid conditions. *J Chem Eng Japan / JCEJ*. 45(6):387–394. <https://doi.org/10.1252/jcej.11we255>
- Wagner C et al. 2001. Mineral paraffins in vegetable oils and refinery by-products for animal feeds.
- Xiao X et al. 2015. Preparation of activated carbon from Xinjiang region coal by microwave activation and its application in naphthalene, phenanthrene, and pyrene adsorption. *J Taiwan Inst Chem Eng*. 53:160–167. <https://doi.org/10.1016/j.jtice.2015.02.031>