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Emerging trends in olive oil fraud and possible countermeasures

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ABSTRACT

A review of most common types of fraud in the olive oil sector has been carried out. The work was supplemented by the results of an international on-line survey of EU and non-EU stakeholders in the olive oil sector. The review confirms that most common infringements (fraud or non-compliance) are the marketing of virgin olive oil as extra virgin, and blends of other vegetable oils (sunflower, corn, palm, rapeseed, etc.) with olive oil being marketing as olive oil. The on-line survey focused on current and future issues facing a range of stakeholders, e.g. exporters, importers, control laboratories. Of seemingly high priority to industry were emerging issues with regards to fraud arising from the addition of deodorized oil and from mixing with oil obtained by a second centrifugation of the olive paste (*remolido*). On the same line, a questionnaire, addressed to the EU Food Fraud Network National Contact Points, highlighted that the most frequent fraudulent practice is mixing with lower quality olive oils and that EU, non-EU and mix of EU and non-EU oils are the cases which need more control activities in relation to false designations of origin.

1. Food fraud: definitions and reporting

In the scientific literature, as well as in many technical reports focused on food authenticity, it is possible to identify different definitions of "food fraud", although to date there is no harmonized definition at a European or international level. In general, food fraud covers cases where there is a violation of food law which is committed deliberately to pursue an economic or financial gain through consumer deception (EU commission website food fraud section: (2016); Serious Fraud Office (SFO) nd,; Food Standard Agency (FSA),; Food and Drug Administration (FDA) - Food Defense,; Elliott, 2014). According to the CEN Workshop Agreement CWA 17369:2019, fraud is defined as "intentionally causing a mismatch between food product claims and food product characteristics". Spink and Moyer (2011) wrote an overview with the intent to provide a base reference document for defining food fraud focuses specifically on the public health threat and to facilitate a shift in focus from intervention to prevention. The authors deconstructed the fraud opportunity using the criminology and behavioral science applications of the crime triangle and the so-called "chemistry of the crime". Rapid Alert System for Food and Feed (RASFF) (2018) database has been the most important tool for exchanging information on food safety and food adulteration issues in the EU. However, some forms of product non-compliance do not sit well with the existing classifications in the RASFF system and need to be addressed by additional means at EU level (Kowalska et al., 2019). In this sense, the EU Food Fraud Network (FFN) and the Administrative Assistance and Cooperation System (AAC) was made available for Member States. Since then, these tools have been working together in synergy to maintain the EU safety and compositional standards for food and feed (2016 - Food Fraud Network Activity Report(The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud, 2016). Every year, a report describing the activities carried out by the EU FFN and the AAC is published (Reports, events useful links, section Food Fraud of the European Commission, 2012). It is important to underline that the list of cases registered by AAC

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does not represent the totality of non-compliances and suspicions of food fraud occurring throughout Europe, as it does not include suspected fraud cases that concern only the national level. According to reports The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud (2017);; The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud (2018); The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud (2019) there is no doubt that the number of requests for assistance and cooperation shared between Member States has increased over recent years. for example members generated a total of 292 requests in 2019 (The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud, 2019). It can also be seen that, when it comes to product categories, differences were recorded among the top 10 notified. In 2019 the category 'Fats and oils' became the first placing 'olive oil' (OO) as the most notified product in the system (The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud, 2019)

The EC identified four operational criteria for appropriate qualification of an instance exchanged in EU FFN and AAC as being food fraud (The EU Food Fraud Network and the System for Administrative Assistance & Food Fraud, 2016). Cases not meeting all the four key criteria are non-compliances within EU food regulation. Between the food fraud databases developed in recent years, a lack of consistency in food fraud categorizations (including adulteration) exists, especially around the criteria of demonstrable intent (Bouzembrak et al., 2018), but each database, despite some limitations (Manning & Soon et al., 2019), is a beneficial source of intelligence that can contribute towards the effective governance of product adulteration.

2. Fraud in the OOs sector: most common and recent kinds of fraud

World OO production in the 2019/20 crop year is estimated to be around 3144000 t and the European Union to be the first producer with an estimated percentage of 63.97% as well as the first exporter and consumer (International Olive Council (IOC), 2019). However, due to its high economic value, as well as its unique sensory, compositional and nutritional characteristics, OO is considered at high risk of non-compliances and fraud. This is mainly related to the extra virgin olive oil (EVOO) higher value, being the top quality and the different price/value of EVOO according with the geographical origin; for example, the EC DG AGRI latest figures for EVOOs, referred to the month May 2020, put the price in oil mill at € 205.9 per 100 kg in Spain, at € 345.8 per 100 kg in Italy and at € 217.5 per 100 kg in Greece (DG AGRI Dashboard, 2020). For the producing Member States, the EU framework for conformity checks (Reg. (EU) 29/2012; Reg. (EU) 1308/2013) effectively contributed and is currently improving the quality of the products on the market, as well as reducing the prevalence of fraudulent practices; those are among the key findings of the study on the implementation of conformity checks in the OO sector throughout the EU (Areté Research, 2020). Nonetheless, the study also highlights disparities and problems in the current conformity check system. Moreover, it stressed that the most common infringements are the marketing of VOO as EVOO, or the marketing as OOs of blends of other vegetable oils (sunflower, corn, palm, rapeseed, etc.) with OO (Areté Research, 2020). To ensure the health and protection of consumers, the Joint Research Center of the European Commission (JRC), as the Commission's internal scientific service, also carries out research into food authenticity. Among these actions, the JRC publishes a monthly summary (Joint Research Center of the European Commission (JRC), with press and media articles on food fraud, with the aim of informing all the stakeholders (consumers, food companies, investors, institutions, etc.) and giving them the opportunity to act on these irregularities. Considering the reports of fraud monthly summarized by the JRC, it can be noted that some categories of adulterated foods capture more media attention than others. However, this output could be an artefact since these are also probably the most highly tested foods and food fraud testing activities may vary in different countries. In particular, the most cited foods which are often subjected to fraudulent activities are those specified by the (European Parliament resolution of 14 January 2014 on the food crisis, fraud in the food chain and the control thereof (2013/2091(INI)), 2014, Regulation (EU), 2017), namely, OO, fish, organic products, grains, honey, coffee, tea, spices, wine, certain fruit juices, milk and meat and those according to the JRC are reported in Fig. 1.

Of the 32 reports concerning OOs (Fig. 1) - of which 20 occurred in Europe - 11 concerned mislabeling, 4 untrue origin, 16 substitution, 6 dilution, 5 intentional distribution of contaminated products/counterfeiting and 1 was related to theft. It should be emphasized that the sum of the different types of fraud appears to be higher than the number of reports, since the single case often presents two different types of issues. For example, one of them, found in the summary of the JRC from September 2018, is related to a product sold as "extra virgin olive oil" (EVOO) which contained seed oil. As a result, this single episode is included in two different types of fraud, one as a case of substitution (prevailing) and one as mislabeling. Almost all types of fraud in the OOs sector (e.g. dilution, substitution, untrue origin) can be considered also cases of mislabeling if those practices are "intentionally" not properly mentioned on the label. Two recurring kinds of fraud for OOs are dilution and substitution, which, in the case of the examined reports, have occurred more in non-EU countries, e.g. in Brazil where the mixing of OO with lampante or soybean oil is very recurrent (Tibola et al., 2018). The fraudulent mixture of OOs with other vegetable oils does not usually lead to health-related problems for the consumers. However, it has been reported that adulteration of vegetable oils caused serious health problems in some cases like Spanish toxic oil syndrome or Spanish OO syndrome due to selling non-edible rapeseed oil as an edible rapeseed oil and even as OO (WHO, 1984; WHO, 1992, p. 42; Posada et al., 1991; Posada et al., 1996; Clemente and Cahoon, 2009; Azadmard-Damirchi and Torbati, 2015). To prevent loss of consumer trust in the image of OO as a high-quality product, a continuous effort at global level is needed to establish and implement appropriate standards and measures against fraud (Rossi, 2017). In fact, OOs are subject to regular monitoring and control for preventing fraud; EU Member States have the possibility to design their risk analysis taking into account several criteria including the OO quality grades, e.g. focusing especially in the commercial category of EVOOs (Reg. (EU) 29/2012; Reg. (EU) 1308/2013). Despite this, the relative technical ease to adulterate the OOs, the appearance of new, emerging and sophisticated frauds, the difference and variability between supply and demand, the different level of control measures applied by countries (Areté Research, 2020), as well as the high commercial value of OOs, are all factors that contribute in making OOs highly susceptible to fraud (Yan et al., 2018). In fact, since the second half of the last century, several investigations have been extensively focused on the implementation of reliable analytical methods to detect frauds in the OO sector. Two examples are represented by the studies carried out by Tiscornia et al. (1985) and Mariani et al. (1987). Recently, Tsimidou et al. (2016) reviewed different cases of adulteration of OO with seed oils or olive pomace oil. Several reports are focused on fraudulent addition to EVOOs of desterolized sunflower oil (Grob et al., 1994; Biedermann et al., 1996) or deodorized OO under mild - or soft - conditions (Aparicio-Ruiz et al., 2017). Moreover, other vegetable oils having a similar fatty acids (e.g. high oleic sunflower oil, high oleic safflower oil) or fatty acids and sterols (e.g. hazelnut) composition or lower price (e.g. palm and avocado oils) have been used as common OO adulterants (Lanzon et al., 1989; Christopoulou et al., 2004; Gallina Toschi et al., 2013; Bajoub et al., 2018). Because of the high price of EVOOs, there is a great temptation to adulterate them; in a review by Azadmard-Damirchi and Torbati (2015), possibilities of adulteration and several detection methods are listed, evidencing drawbacks for some of them to detect specific adulteration. Despite being very old frauds, among the most recently reported cases of OO fraud, are those where sunflower oil, artificially dyed with beta-carotene or copper

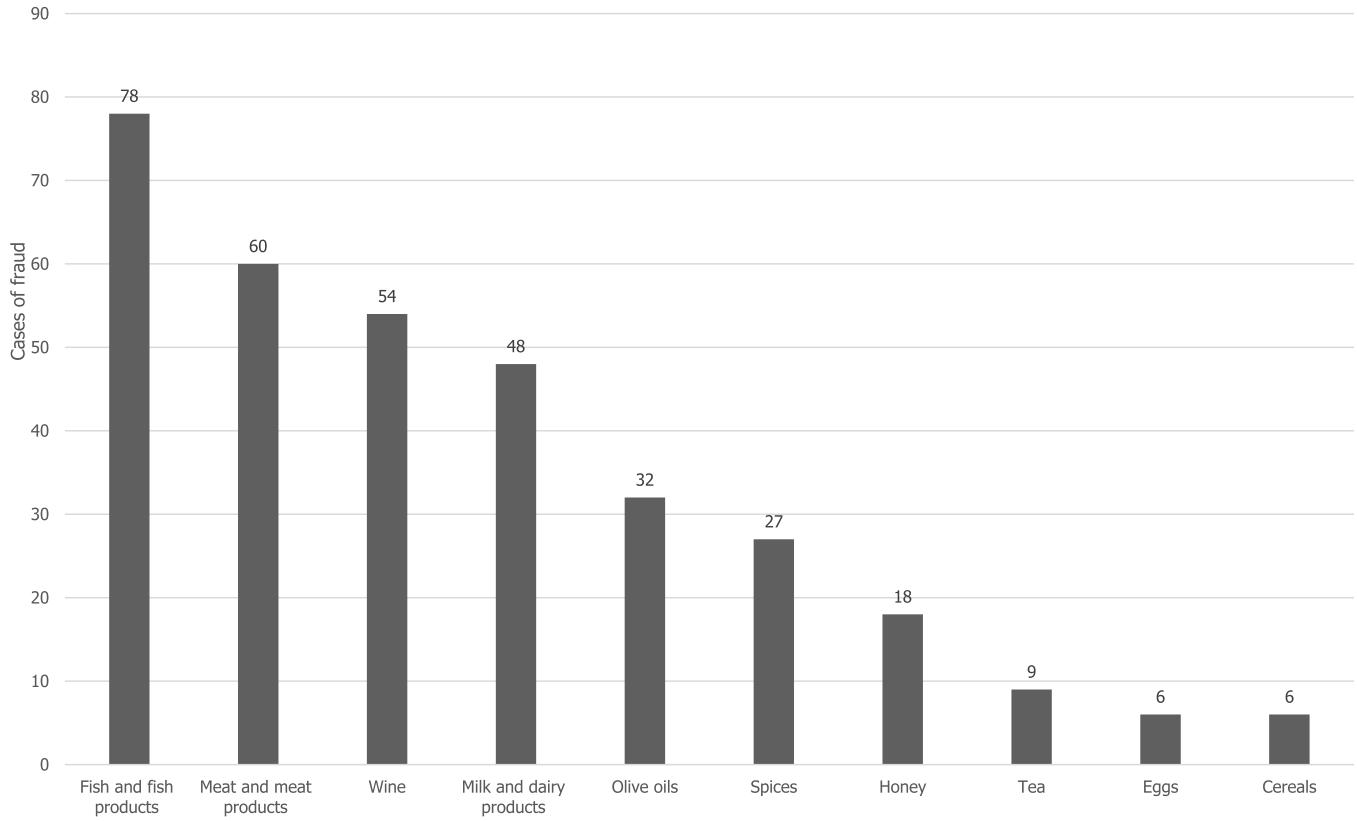

Fig. 1. Reports in press and media articles of fraud as food product categories registered from September 2016 to December 2019 in JRC monthly summary of articles on Food Fraud and Adulteration.

complex of chlorophyll (e.g. E141) to mime the color of OO, was used as a substitute or to dilute the product (Fang et al., 2015). It is also often reported that EVOO can be misbranded or, more in general, can be mislabelled with respect to the quality declared on the label (Gallina Toschi et al., 2013; Tsimidou et al., 2016). Fraud cases affecting OOs are wide ranging, as evidenced by the results of the quality controls and anti-fraud inspections carried out between 2011 and 2014 by the Government of Catalonia (in Spain), discussed in the article by Cugat and Biel (2016). In this work, cases of production and marketing of oils labelled with a protected designation of origin (PDO), but produced from olives harvested in areas outside the PDO as well as oils with a denomination on the label that does not correspond to the real one, are reported. Among the others highlighted by Cugat and Biel (2016), mislabeling, dilutions and unauthorized enhancements specifically related to the composition of the oils detectable through quality and purity parameters, as well as false declarations on the labels (or labels made in a way that does not comply with the legislation), are listed in Table 1.

Table 1
Examples of mislabeling, dilutions and unauthorized enhancements specifically related to the composition and false declarations on the labels of OOs by Cugat and Biel (2016).

Examples of mislabeling
Oils sold as EVOOs and VOOs but corresponding to a lower quality product category based on the sensory analysis results (Panel test).
OOs bottled as virgin, but already with a peroxide value higher than the limit demonstrating an impairment of the oxidative state.
Examples of dilutions
EVOOs in which the presence of stigmastadienes has been detected above the limits, indicating a probable mixing with refined vegetable oils.
OOs (as products obtained from the blend of VOOs with refined oils) produced with the use of non-compliant refined OOs.
Examples of unauthorized enhancements
Oil sold as EVOOs, but containing coloring additives (e.g. E175).
Oil sold as OOs, but containing seed oils with added dyes (e.g. E160, beta-carotene).
Examples of false declarations
OO packaged in unsealed containers, not properly labelled or unlabeled.
Misleading sales descriptions.
Inappropriate use of the PDO.
Mentions of organic and integrated production in oils obtained from conventional agricultural system.
False declaration of origin for olives or VOOs.
False declaration of the variety of olives.
Lack of adequate documentation to confirm the information declared on the label regarding the origin of the oil, the variety of olives and the production method.
Illegible label.

3. Recently reported incidents

In addition to Rapid Alert System for Food and Feed (RASFF) (2018), a number of databases exist that collect data and monitor problems related to the safety and authenticity of food products. An example is HorizonScan (HorizonScan,), a proprietary tool owned by Fera, a global system that helps the food industry to stay alert by identifying and assessing the risks across all food integrity areas as well as providing unseen insight into the supply chain. A search performed February 14, 2020 on this platform, using "olive oil" as keyword, reported 69 records, of which 7 are from the RASFF and 62 from other sources. Of these records 13 correspond to piece of news in the press, concerning non-compliance and OO fraud; some of these items are reported here as an example: 1) April 10, 2017 - From the analyses carried out on 35 EVOOs sold in Danish supermarkets, it appears that only 6 were extra virgin, 15 were virgin and the remaining 12 lampante OOs. 2) April 25, 2017 - In the last 2 years, the Brazilian Ministry (MAPA) has detected irregularities in 45 commercial brands of EVOO. Out of 333329 L analyzed, 205579 were found to be characterized by sensory defects (virgin or lampante OOs). 3) September 25, 2017 - One third of the 131

OO samples analyzed between 2015 and 2016 in the United Kingdom was found to be non-compliant with one or more chemical parameters or organoleptic analysis. 4) November 29, 2017 - The Greek police arrested 7 people following an investigation into the adulteration of an OO. The criminal organization had added green dye to sunflower oil, and then sold it under various brands in Greece and other European countries; five tons of unpackaged oil were seized, as well as another 12 tons were just about to be exported. 5) July 24, 2018 - Spain's largest OO cooperative was under fire for its importing practices. The fine originated from outstanding import tariffs that this company failed to pay on OO it had imported from Tunisia and Morocco. The imported oil was then blended with low quality Spanish OO that had been obtained in second extractions from olives used in the production of EVOOs. This blend was then sold as VOO in the United States at prices 40 percent lower than other Spanish and Italian OO and up to 100 percent lower than OOs from California.

The Food Authenticity Research Network Hub (FARNHub,) is a web-based platform developed within the EU H2020 AUTHENT-NET Project (Grant agreement No. 696371) where users can get an overview of currently available resources related the authenticity of foods for each country. Searching with the keywords "olive oil" it is possible to consult the articles in the database related to fraudulent incidents and non-compliances involving this product. In the period between 2015 and 2019, a total of 185 articles are identified in this database: here are listed, only by way of example, three episodes occurred in the same period, extracted from as many articles in the web. 1) January 2015 - Based on the chemical and sensory results, four out of six of the best-selling EVOOs in Norway did not turn out to be extra virgin but virgin, as they were characterized by sensory defects, such as musty and rancid. 2) December 2015–7000 tons of product were sold on the Italian and international markets, in US and Japan, as "100% Italian" EVOO when in reality it was oil mixed with oils from non-EU countries, such as Syria, Turkey, Morocco and Tunisia. Fraud was unmasked between Brindisi and Bari (Italy) by the Italian State Forestry Corps, and the District Anti-Mafia Directorate (DDA) of Bari. 3) February 2016 - Over 2000 tons of OO improperly labelled as Italian. The fraud case concerns the falsification of documents attesting the Italian origin of EVOO which was Spanish and Greek.

3.1. Stakeholder survey on emerging frauds: discussion of the received answers

The combination of increasing competitiveness, expanding markets with a different level of implementation of the regulations has been exploited by counterfeiters. In this context, a H2020 research project, OLEUM, was commissioned in September 2016 by European Commission to address these issues(H2020 SFS-14a, 2014). To check for vulnerable aspects in the current regulations and analytical methods and to look for information about current and emerging fraud in the OO sector, a online survey was carried out to collect information and opinions from stakeholders on emerging issues. The questionnaire, which was prepared in 5 different languages (English, French, Greek, Italian and Spanish), was sent by e-mail during 2018 to over 200 stakeholders in the OO sector. The study was conducted in agreement with the Italian ethical requirements on research activities and personal data protection (D.L. 30.6.03 n. 196). A total of 111 completed questionnaires were returned from both European (87 questionnaires) and non-European (24 questionnaires) countries (Fig. 1Sa). Most of the questionnaires were filled in by people working in: the OO sector for company control laboratories (32); involved in research activities in university, public and private research institutions (28) and from official control laboratory personnel (15) (Fig. 1Sb). The received results to the questionnaire are reported in a dataset (Casadei et al., 2021).

At first, the questionnaire asked about OOs obtained through illicit mixing. Respondents had to mark the answer giving a priority from A (highest priority level) to C (lowest priority level) according to the needs of efforts in fighting different fraudulent cases (Fig. 2a). In general, respondents' answers highlighted the primary relevance of addressing efforts in fighting fraudulent cases related to illegal mix of OOs with deodorized oils (Fig. 2a). The fraudulent mixing with oils extracted from olive fruits by different technologies (e.g. *remolido* and pomace) or low quality oils (e.g. lampante) was generally viewed as a lower priority issue compared to the mixing with selected blends of different vegetable or deodorized oils. A deeper analysis was also performed to split all the respondents' answers into subgroups according to the professional area and to make comparisons among them. Fig. 2b and c show some differences between official control and company control laboratories: the first considered fraudulent mixing with selected blends of different vegetable oil as the highest priority. On the contrary, the latter evaluated the illegal mixture with deodorized oils at highest level of priority (Fig. 2b). A higher level of consensus to consider mix with oils extracted from olive fruits by different technologies (e.g. *remolido* and pomace) or low quality OOs (e.g. lampante) as the lowest priority level was also observed except company importers (Fig. 2c).

Subsequently, the questionnaire asked to give a priority from A (highest priority level) to C (lowest priority level), according to the needs of efforts in fighting different fraudulent cases, for the mix with oils extracted from olive fruits by the above mentioned different technologies (Fig. 3a). A good agreement can be found among the answers given by the respondents: data clearly shows that most respondents consider the use of *remolido* or lampante oils as the most important issue to fight regarding illicit mixing with oils extracted from olives fruits by different technologies or with low quality OOs (Fig. 3a). On the other hand, the use of pomace oil does not appear to be the top priority. Subgroup analysis (Fig. 3b) reveals the good agreement among responses provided for priority level A towards mixing with *remolido* oils, with the exception of data received by researchers and official body control laboratories where the highest priority was assigned to the fraudulent mixing with lampante oils. To clarify, *repaso* and/or *remolido* oils are obtained when the pomace is transferred to a second decanter capable of still extracting 2–2.5% of oil (Hermoso et al., 1999). Considering these priorities given by the respondents, in the future it will certainly be important to develop ad hoc methods that can identify this type of fraud to identify mixtures with lampante or *remolido* oils (Cerretani et al., 2011).

Fig. 4a shows the frequencies related to the priorities in addressing efforts to fight OOs fraudulent cases over faked declaration of origin. Respondents replied giving a priority from A (highest priority level) to B (lowest priority level) taking into account to the needs of efforts in fighting different fraudulent cases. Survey respondents were asked to give a priority scale to two different kinds of declarations of origin affected by fraud: Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI), versus EU, non-EU and a mix of them. According to the replies, it is not possible to clearly assign a higher priority to one of these two categories of faked declarations of origin. The graph (Fig. 4b) also shows a good agreement among respondents belonging to different professional area in giving the highest priority to EU, non-EU or mix of them respect to PDO and PGI, with the only exception of researchers. To date, despite the European regulation has established specific rules to report the geographical origin of EVOOs and VOOs on the product label, an official analytical procedure to verify the origin has not been yet defined (Palagano et al., 2020). The verification of the declaration of origin is based on documentations.

Fig. 5a shows the frequencies related to the priorities given about addressing efforts to fight faked declaration of monovarietal OOs, according to the professional areas of the respondents to the questionnaire. A clear majority of respondents finds of medium relevance to address efforts in fighting frauds related to faked declaration of monovarietal OOs; about 10% of respondents do not consider it a priority. On the other hand, some differences can be observed between, from one side, official, private and company control laboratories subgroups and, to the other side, the subgroups including exporter/importer companies and

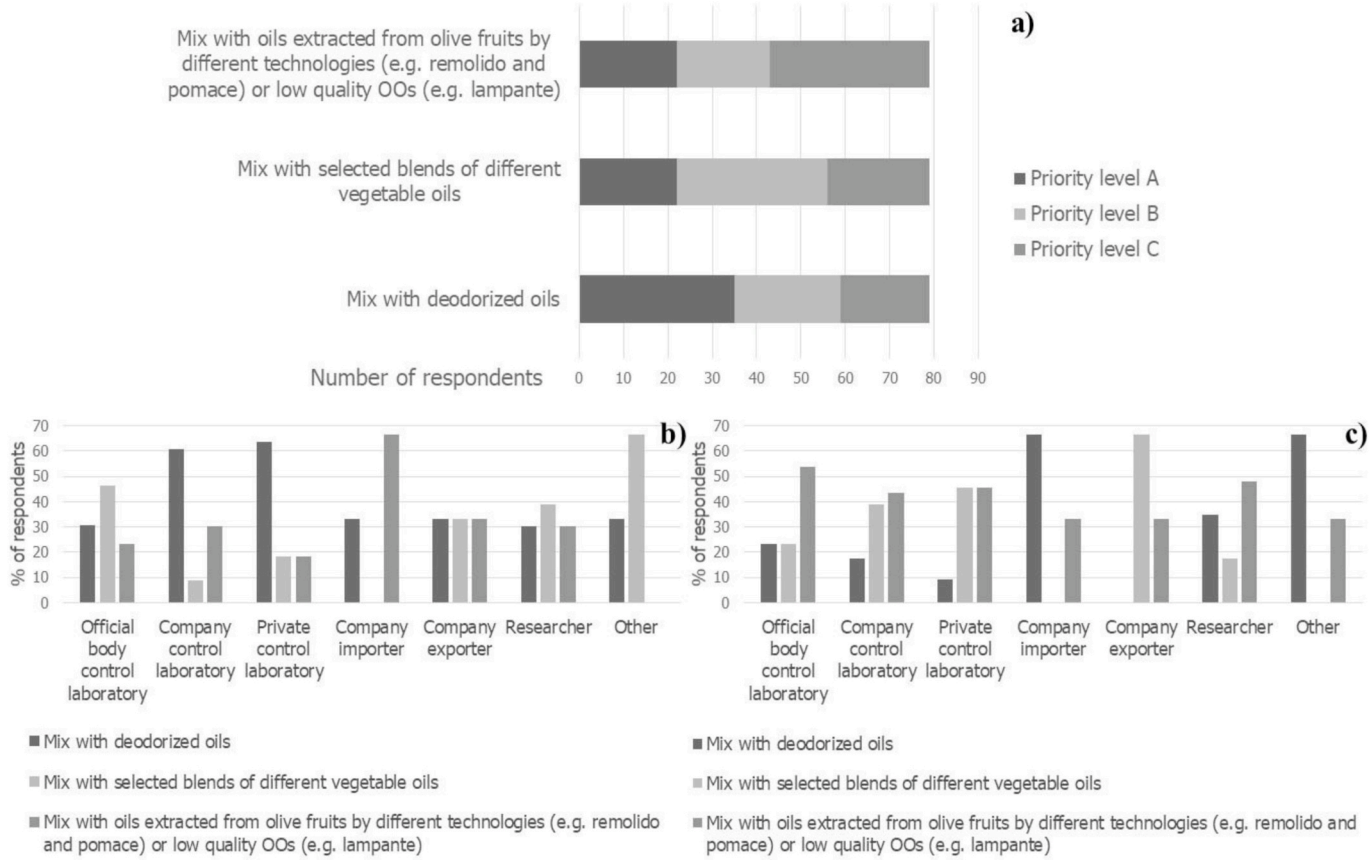

Fig. 2. **a)** Frequencies related to the priorities in addressing efforts to fight OOs fraudulent cases related to illicit mixing of OOs, according to the respondents to the questionnaire; **b)** frequencies related to the highest priority given about addressing efforts to fight OOs fraudulent cases related to illicit mixing of OOs, according to the professional areas of the respondents to the questionnaire; **c)** frequencies related to the lowest priority given about addressing efforts to fight OOs fraudulent cases related to illicit mixing of OOs, according to the professional areas of the respondents to the questionnaire.

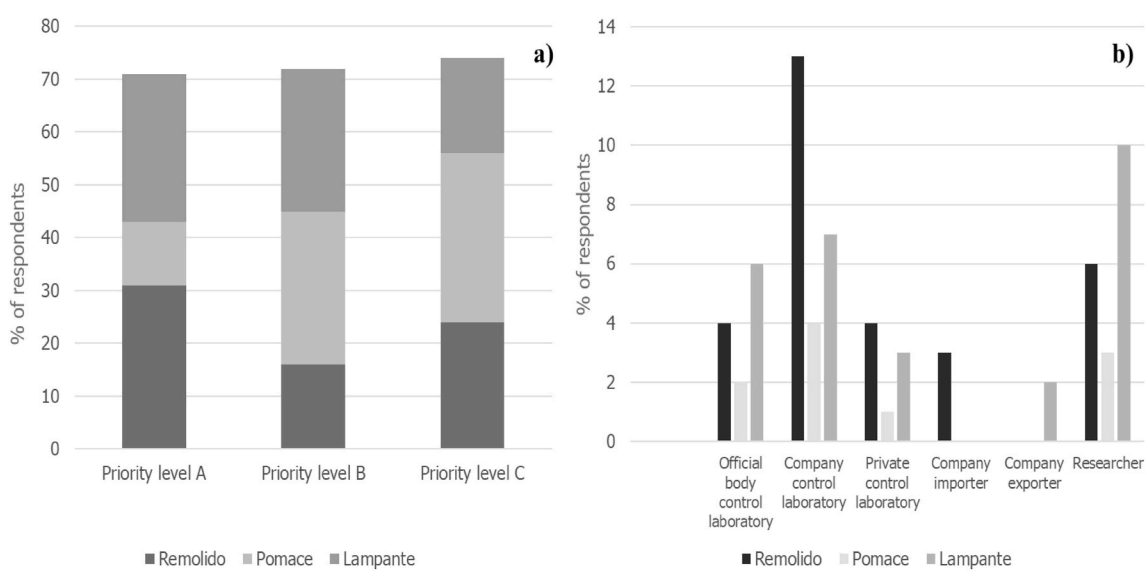

Fig. 3. **a)** Frequencies related to the priorities in addressing efforts to fight OOs fraudulent cases related to mixing with oils extracted from olive fruits by different technologies, according to the respondents to the questionnaire; **b)** frequencies related to the highest priority given about addressing efforts to fight OOs fraudulent cases related to illicit mixing with oils extracted from olive fruits by different technologies, according to the professional areas of the respondents to the questionnaire.

researchers (Fig. 5b). The latter consider that the faked declaration of monovarietal OOs is a more important issue compared to the former subgroups. Maybe this is due to the small market share of monovarietal oils and, on the contrary, their biodiversity meaning, raising the interest of researchers and specific companies. At the end of the questionnaire, participants were asked if they would like to point out any other

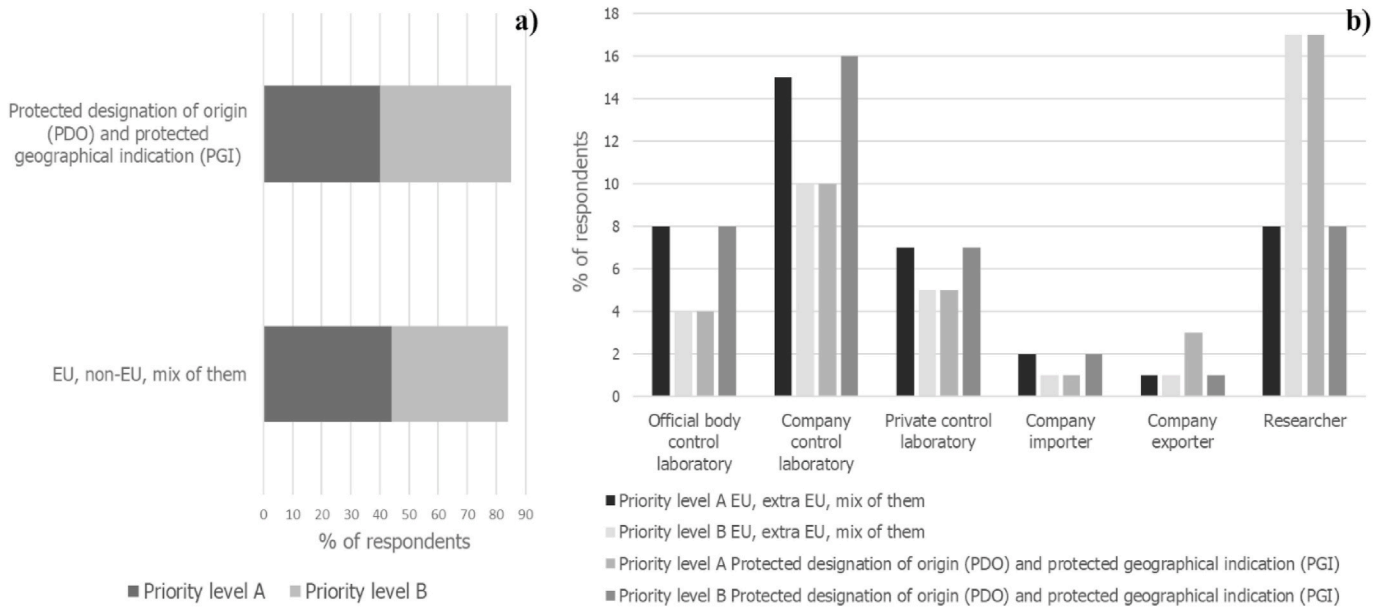

Fig. 4. **a)** Frequencies related to the priorities in addressing efforts to fight OOs fraudulent cases related to faked declaration of origin, according to the respondents to the questionnaire; **b)** frequencies related to the priorities given about addressing efforts to fight OOs fraudulent cases related to faked declaration of origin, according to the professional areas of the respondents to the questionnaire.

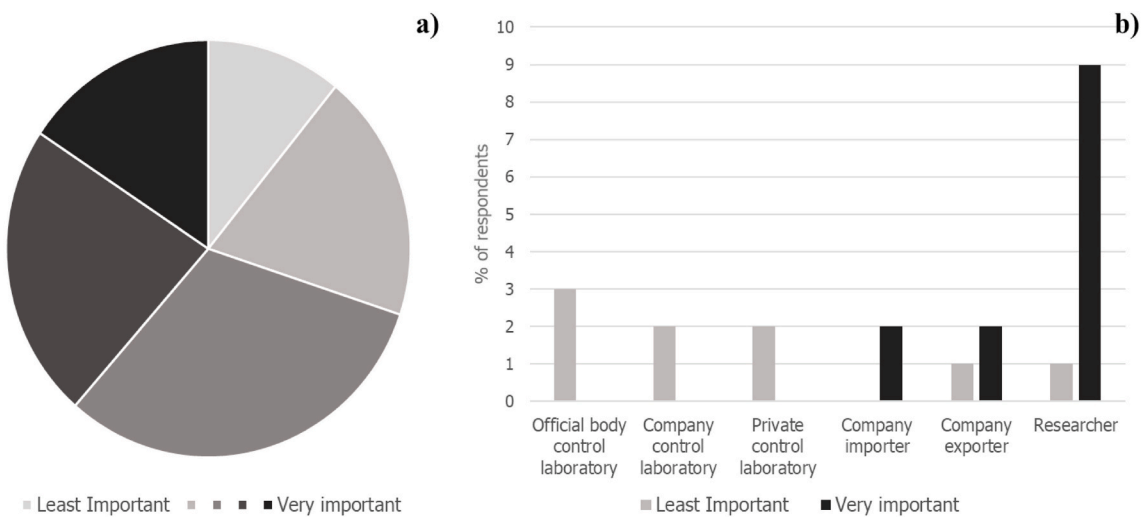

Fig. 5. **a)** Frequencies related to the priorities given about addressing efforts to fight faked declaration of monovarietal OOs, according to the professional areas of the respondents to the questionnaire; **b)** frequencies related to the priorities given about addressing efforts to fight faked declaration of monovarietal OOs, according to the professional areas of the respondents to the questionnaire.

common and emerging kind of fraud not considered in the previous questions. In some cases, respondents highlighted the problem of illicit mixing procedures (mix with lampante OOs, old OOs, use of vegetable oils other than OOs in refined OOs, among others) as well as the use of fraudulent procedures aimed at modifying the natural colour and aroma of the oils.

3.2. The questionnaire on the common and emerging fraud issues addressed to the EU Food Fraud Network (FFN) national contact points

In order to support the OO sector, under the guidance of the European Commission DG AGRI (Unit G.4 – Arable crops and OO) and DG SANTE (Unit G.5 - Alerts, Traceability and Committees), a questionnaire specifically addressed to the EU FFN National Contact Points has been developed and sent during 2018 (Table 1S). The aim was to acquire consolidated reports by the control bodies on the occurrence of common and emerging fraud issues. The EU FFN consists of national contact points in the 28 EU Member States, Switzerland, Norway and Iceland together with the European Commission. Each Contact Point of the EU FFN is representing the authority designated by each EU Member State for ensuring cross-border administrative cooperation with their counterparts in the other EU Member States in matters of suspected intentional and economically motivated violations. The average time taken to complete the questionnaire was around 15 min and 17 replies (out of 31 questionnaires sent) were received from: Croatia, Cyprus, Czech Republic, Denmark, Estonia, Ireland, Italy, Lithuania, Norway, Poland, Portugal, United Kingdom, Slovakia, Slovenia, Spain, Sweden and Switzerland.

Regarding question 1 (Table 1S) 8 respondents replied that they encountered no fraud cases in the last 12 months, while 1 respondent highlighted a difficulty in providing a number as answer to this question. This was due to the absence of a legal definition of food fraud at both, an

EU and international level and for that reason some respondents identified the need of a more clear understanding on the use of this concept also in the OO sector. Four respondents replied to this question without distinguishing between "non-compliance" and "fraud cases", while 4 provided a specific number; considering these observations, the question 1 was misunderstood, and it is not possible to provide an overall view of the given answers. According to the respondents who have answered to question 2 (6 out of 17) (Table 1S), the most frequent fraudulent practice related to mixed OOs at national level is "mix with lower quality (e.g. virgin for EVOO or lampante for virgin) OOs" followed by "mix with different vegetable oils or selected blends of them" and "mix with olive-pomace oil and OOs obtained by second centrifugation of olive pastes (*remolido*)". The less frequent one was related to "mix with refined OOs, including soft-deodorized oils". The lack on widely accepted biomarkers for soft-deodorized oils, as mentioned below, is perhaps the most relevant reason why this is not targeted by official control labs. For question 3 (Table 1S), considering each national market, based on the answers received (9 out of 17), EU, non-EU and mix of EU and non-EU oils are the cases which need more control activities in relation to false designations of origin, followed by the ones related to specific country of origin and finally by OOs with PDO and PGI. Eight Contact Points of the EU FFN answered question 4 (Table 1S) and 4 respondents said that they had no data available to comment this request. Most of them highlighted that not listed fraudulent practices frequently occurring are adding green dye (e.g. chlorophyll) to sunflower oil to give it the appearance of OO and the false designation of origin (e.g. 100% Italian) and, finally, on the basis of the received answers to question 5 (15 out of 17) (Table 1S), it can be observed that the EU regulation on OO is generally considered the most extensive and concrete, in terms of analytical methodologies to ensure OO quality and authenticity. However, it was also highlighted by respondents some criticalities, thus there is room to improve and intensify the controls. Some of the respondents indicated specific fraudulent practices related to OO that are occurring due to the lack of appropriate analytical methods, these issues, as well as possible solutions proposed by the respondents, are listed below:

a) False designation of origin: a possible solution suggested by the respondents could be the establishment of a specific databank of isotopic values (H/D, $^{13}C/^{12}C$, and $^{18}O/^{16}O$) like the one already in place for wine (Reg. (EU) 2018/273 and Reg. (EU 2018/274)). In Italy, on behalf of the Ministry of Agriculture, Food and Forestry, the Edmund Mach Foundation has built up a database for PDO EVOO (Camin et al., 2009). Furthermore, the FATG-DB04 database of fatty acid and triacylglycerol composition (FRANCE OLIVE - Association Française Interprofessionnelle de l'Olive,) was built in the 2000's by French researchers from the Olive Tree Technical center (CTO) and the French Olive Professional Association (AFIDOL) for identifying the varietal origin and eventually the geographical origin. Reference EVOO samples with different varieties and origin, traceability and mandatory information on labels (for example indication on specific country of origin, EU or non-EU origin) might be also helpful tools according to the respondents.
b) Soft deodorization: new analytical markers are requested by respondents for detecting soft deodorized OOs and their illegal blends with VOOs. In summary, soft deodorization consists of a technological process practiced on VOOs with feeble sensory defects in order to remove or reduce these off flavors. The commercialization of OOs labelled as top-quality grade (EVOO), but actually obtained by blending soft deodorized oils with EVOO, is an illegal practice. As the technological conditions (e.g. temperature and pressure) applied in this fraudulent procedure are "mild", they avoid the formation of typical markers of refining (such as stigmastadienes or *trans* isomers of fatty acids) in treated oils, thus it is very difficult to detect this type of fraud (Conte et al., 2019). The determination of the content in fatty acid alkyl esters (methyl and ethyl esters) (FAAEs) was firstly introduced by the International Olive Council (IOC) in 2010 (COI/T.20/Doc. No 28) and then adopted in the official method by the European Union in 2011 (Reg. (EU No 61/2011)) undergoing some revisions over the following years, limiting the measurement to ethyl esters, only (Reg. (EU No 1348/2013)). Fatty acid ethyl esters (FAEEs) are formed in oils coming from olives that have undergone a sugar fermentation process, leading to the production of ethanol (Perez-Camino et al., 2002). If low quality VOOs, e.g. with weak defects, are soft deodorized, the FAEEs content is not significatively reduced, resulting in this parameter being useful to detect soft deodorized OOs with fermentative defects. Nowadays, FAEEs represent the only officially recognized markers, even if indirect, for detecting the illegal process of soft deodorization (Conte et al., 2019). In this context a newly validated in-house method for determining the FAEEs has been proposed to speed the preparative steps of the official method (Palagano et al., 2020). Furthermore, other new parameters based on free acidity and diacylglycerol content have been proposed (Gómez-Coca et al., 2020) for the detection of this fraudulent process, particularly useful when soft deodorization is applied to VOOs affected by non-fermentative defects (e.g. rancid).
As the FAEEs content is the only regulated indirect marker for the identification of soft deodorized OOs and their illegal blends with VOOs, it is desirable that other national (e.g. Californian and Australian standards) and international regulations (Codex Alimentarius) also adopt this parameter to harmonize trade standards and combat a globally diffused fraud.
c) Mislabeling of quality grades: respondents highlighted the need of new tools, parameters and markers able to support the sensory analysis of VOOs (Panel test). Among them, volatile organic compounds (Barbieri et al., 2020; Quintanilla-Casas et al., 2020; Valli et al., 2020) and sensory reference materials, are very relevant to support the organoleptic evaluation of VOOs.
d) Intentional falsification in terms of packing of lower quality oil: in order to maintain the quality of the oil, guidelines for more precise specification of the declared condition would be welcome (e.g. the term "cold" with the temperature interval in °C and "dark" with the illuminance interval in lux). To answer this request, IOC has recently released the "best practice guidelines for the storage of OOs and olive-pomace oils for human consumption" (IOC, 2018), detailing point by point the best conditions to be guaranteed before the bottling and during all the oil shelf-life.

In the context of detection of fraud and control of OO quality, the harmonization of global regulations will be very important, with the ultimate goal of strengthening official controls.

Finally, it is crucial to continually update and improve the analytical and regulatory frameworks to try to keep up with the fraudsters.

4. Conclusions

Over the last three decades, the European Union has taken considerable measures to counteract food fraud. Among them, the AAC allowing requests for assistance and cooperation to be shared between Member States has demonstrated the need for transnational cooperation among the competent authorities in the Member States.

The peculiar sensory attributes, the physic-mechanical processes for its production, its reputation as one of the healthiest sources of dietary fats and minor compounds (e.g. polyphenols) and cornerstone of the Mediterranean diet make OO a food with a high commercial value and attractive for consumers, but at the same time a prime target for fraudsters. It should not be forgotten that OO is a product that, due to its "liquid form", can be easily mixed and accompanied by a falsified documents; even if better and better systems for the traceability are available, e.g. the Italian SIAN (MIPAAF - SIAN), these are still not capable of completely keeping track, qualifying and geolocalising all the OO volumes produced.

From the analysis of the reports, papers and questionnaires discussed

in this critical review, it is evident how EVOO, the top VOO category, remains one of the most highly targeted by fraudsters, on the market. Again, by the answers received to the OLEUM on-line survey (sent to EU and non-EU stakeholders of the OO sector), the results highlighted the primary need in fighting fraudulent cases related to illegal mix of EVOOs with deodorized, *remolido* or lampante OOs as the most important issues to counteract. However, it is not possible to estimate with certainty what is the proportion of deodorized or *remolido* OOs that circulates (fraudulently) on the global market, as these practices are illegal. What is certain is that the quantity of virgin and lampante OO produced is very high and that the price differential is significant e.g., € 41.8 and € 10.9 in Spain, € 195 and € 40.7 in Italy and € 99.4 and € 28.4 in Greece for lampante and virgin OO with respect to EVOO (DG AGRI Dashboard, 2020), thus representing a considerable temptation for fraudsters. This concern was evidenced from the results of the questionnaire on the update and delivery of the appearance of common and emerging fraud (addressed to the EU FFN National Contact Points) pointing out that the most frequent fraudulent practice related to mixed OOs is "mix with lower quality OOs". Another hot issue underlined by the answers to the questionnaire regarded the false designations of origin e.g. non-EU for EU or mix of non-EU for EU.

The picture that comes out of from this complex scenario is that, on the one hand, the EU regulation dealing with OO is one of the most extensive and contains a suite of analytical methodologies to ensure OO quality and authenticity are appropriate, despite some deficiencies. An information that is important to pass to the consumer is that the level of attention and the high request in terms of conformity checks have currently improved the quality of the OO on the market in the last thirty years. On the other hand, the results of this review indicate that, to better guarantee OO quality and authenticity, there is still the need to ameliorate conformity checks, reduce the cases of disagreement in the classifications, develop improved robust methods and supportive screening tools, in an attempt to try to be one-step ahead of fraudsters. A promising way that IOC, EU and other regulatory bodies could take includes: i) a joint strategy able to combine sensory and instrumental data useful, in particular, in cases of disagreement between two panels; ii) an improvement of the proficiency and alignment of the panels by a mutual calibration achievable e.g. by finding the same sensory reproducible reference materials on the market. Furthermore, given the actual possibility to handle large set of data, real and virtual compliant compositions can be stored in a repository of validated data (e.g. OLEUM databank under development) and used as quality and authenticity references. In addition, the quality and authenticity information of a certain OOs could be put in relation with volumes produced and their geolocation; thus the intersection between official quality controls and traceability, typical of a blockchain scenario, could be the next fraud countermeasure.

CRediT authorship contribution statement

Enrico Casadei: Formal analysis, Conceptualization, Methodology, Investigation, Data curation, Writing - original draft. **Enrico Valli:** Conceptualization, Writing - review & editing, Supervision, Project administration. **Filippo Panni:** Formal analysis, Investigation. **James Donarski:** Formal analysis, Investigation. **Jordina Farrús Gubern:** Formal analysis, Investigation. **Paolo Lucci:** Formal analysis, Investigation. **Lanfranco Conte:** Writing - review & editing. **Florence Lacoste:** Writing - review & editing. **Alain Maquet:** Writing - review & editing. **Paul Brereton:** Writing - review & editing. **Alessandra Bendini:** Writing - review & editing, Supervision, Project administration. **Tullia Gallina Toschi:** Conceptualization, Writing, Supervision, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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