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Fish Discards Management: Pollution Levels and Best Available Removal Techniques

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Abstract

Fish discards and by-catch issues are highly topical subjects nowadays permanently under a social focus. To manage this issue, two main approaches are being considered to address this discard problem: reducing by-catch and increasing by-catch utilization. As these two harvesting strategies may be complementary, an appropriate balance between by-catch reduction and utilization is desirable for any fishery.

Increased by-catch valorization interest may come from a greater demand for fish products: the development of new markets for previously discarded species; the use of low-value by-catch specimens for aquaculture and animal feed or the creation of value-added fish products from by-catch or discarded fish for food, pharmaceutical or cosmetic industries. In this valorization framework, and always targeting the aim of promoting the responsible and sustainable management of marine resources, pollutant levels in catches of European fisheries (including target and main discarded species), as well as the best available decontamination techniques of marine valorized discards/by-products are compiled and analyzed in this work. This is due to the fact that a wide different distribution of pollutant concentration between tissues in fish can be found, especially in detoxifying organs, like kidney and liver and in other fractions of high lipid content, like skin. Therefore, contaminants present in fish discards may be transferred to the valorized products obtained from them, leading to possible long-term bioaccumulation and subsequent adverse health effects.

The objective of the present work is to provide a general view of the present discards/by-catch valorization-based management options.

Keywords Fish discards; sustainability; pollutants; removal techniques; valorization

1. Introduction

Most of Persistent Organic Pollutants (POP) and heavy metals emitted to air or water as products or by-products of industrial activities, or applied directly on land (i.e. pesticides) can travel long distances from its primary source, and can finally end up in the marine environment (*1*,*2*). Most common examples of these substances are polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF), polychlorinated biphenyls (PCB), polycyclic aromatic hydrocarbons (PAH), organochlorine pesticides (OCP) (like hexachlorobenzene - HCB, hexachlorocyclohexanes - HCHs, dichlorodiphenyltrichloroethane - DDTs, and metabolites like dichlorodiphenyldichloroethylene - DDE), polybrominated diphenyl ethers (PBDE), hexabromocyclododecanes (HBCDs) and metals like As, Cu, Cd, Zn, Pb and Hg. Due to their persistence and toxicity, they can accumulate in biota and biomagnify through trophic webs, being biomagnification especially important for aquatic organisms (*3*,*4*).

Many studies in the scientific literature, like surveys of fish and fish products in markets of different countries (*5*-*8*), monitoring reports of Public Administrations and the EU (*9*), as well as web tools like the EcosystemData of ICES (http://ecosystemdata.ices.dk/), reported significant levels of this kind of pollutants (especially of dioxins, PCBs and heavy metals) in several cases for commercial species of different fisheries. Many of these studies have been developed in heavily polluted areas like the Baltic and North Seas (*10*-*12*). Hence, it is logical to assume the presence of contaminants in other non-commercial species, although contamination levels in these non-targeted and/or discarded species are not usually assessed. However, a sustainable management of discards passes through the evaluation of their pollutant content, since the most common uses of discards are oriented to both the production of fish oil and meal (for aquaculture/animal feeds) or as additives in human direct consumption products (food supplement, margarines, gelatine, etc.). In fact, pollutant amounts found in some marine valorized by-products are of concern (13). On the other hand, some studies revealed that concentration of POPs is significantly higher in farmed fish (mainly salmon) than in wild fish (*14-16*). This is due to the presence of pollutants in feed, which comprise fish oil and meal (*17*). Concerns on this issue have led EU to set maximum levels for dioxins and dioxin-like (DL-) PCBs for aquaculture feeds (*18*), fish and fish products (*19*)

For fulfilling these regulations, different options are available to the fish farming industry. One possibility is to use fish oils or meals presenting low levels of these pollutants for fish feed, for example, from the southern hemisphere (*20*). However, this is not the optimal approach, since fish oil availability is already limited (*21*). Another solution is to employ vegetable oils in the feed, but these oils do not contain the fatty acids that represent the positive nutritional properties of marine food, and thus, fish breeding with vegetable oils results in specimens with worse performance, health and quality. In fact, a mixture of oils is usually employed as compromise solution (*20,22,23*). Finally, pollutants could be removed from the oils and meals used in fish feeds, while retaining the nutritive components of the oil (*21*). Therefore, research and development of technologies for the removal of these contaminants has gained considerable importance (*17*), since market demand for decontaminated fish feeds in aquaculture has increased during last years (*20*). Most studies on pollutant removal techniques are focused on the reduction/elimination of POPs (dioxins and dioxin-like polychlorinated biphenyls) in fish oils, especially those produced for salmon breeding. Less attention has been paid to fishmeal, and none to other valorized fish products, like gelatin or hydrolizates. Taking into account the lipophilic character of pollutants, their levels on this type of proteic products should not be of concern.

In the aim of promoting the responsible and sustainable management of the European fishing activity, actions were directed to the development of policies to reduce unwanted by-catches and eliminate discards in European fisheries, as well as to make the best possible use of the captured resources avoiding its waste. In this sustainability framework, FAROS project, co-funded under the LIFE+ Environmental Program of the European Union (LIFE08 ENV/E/000119 – www.farosproject.eu), aims as one of its main objectives to analyze the valorization potential of fish discards in order to contribute to their sustainable management by minimizing discards/by-catch through their optimal valorization to recover and to produce valuable chemicals of interest in the food and pharmaceutical industry (*24*). In order to properly define these adding-value processes, the key issues of pollutant levels in catches of European fisheries (including target and main discarded species), as well as the best available decontamination techniques of marine valorized by-products were compiled and analyzed from several studies, with the objective of providing a general picture of the present management options.

2. Pollutant content in species of European fisheries

2.1. Existing pollutant profiles

To date, Ecosystemdata web tool of ICES (http://ecosystemdata.ices.dk/) can be considered one of the most complete infrastructure of marine data compilation corresponding to the European fishing area. A search within this database was developed for all the discarded species (159) identified in the fisheries considered in FAROS project (*25*):

a) Galician bottom otter trawl fleet vessels authorized to fish in Community waters targeting flat fish, and basically operating in Great Sole Bank.

b) Galician coastal bottom otter trawl fleet vessels targeting a variety of demersal species.

c) Portuguese coastal bottom trawl vessels for demersal fish that operate along the year, with hauls directed to a variety of species.

The objective was to check which “FAROS species” (main discarded species in these fisheries) were found in the database, and if present, which ones were monitored on pollutant profiles. The qualitative results of this query are shown in Table S1 of the Supplementary Material. It can be seen that pollutant analyses are only available for 25 of the 159 species reviewed. Among these 25 species, only 7 correspond to the 29 main species discarded in the Spanish and Portuguese *métiers*, marked on grey in Table S1 (*25*). These species are: *Chimaera monstrosa* (rabbit fish), *Lepidorhombus whiffiagonis* (megrim), *Melanogrammus aeglefinus* (haddock), *Merluccius merluccius* (hake), *Micromesistius poutassou* (blue whiting), *Scomber scombrus* (Atlantic mackerel) and *Scyliorhynus canicula* (small-spotted catshark). Moreover, *Micromesistius poutassou* and *Scyliorhynus canicula* were only monitored for heavy metals and Hg alone, respectively. The remaining 18 pollutant-monitored species included in Table S1 are considered as discards in these métiers only in few occasions, i.e., at a very low discard rate. In fact, most of them have an important commercial value, hence the reason of their exhaustive monitoring on pollutants. Examples of these species are *Gadus morhua* (cod), *Merluccius merluccius* (hake), *Coryphaenoides rupestris* (roundnose grenadier), *Hoplostethus atlanticus* (orange roughy) or *Lophius piscatorus* (monkfish). Besides, flatfish or species that live on or within the sediment layer (bottom dwelling fish) and deep sea fish are among the monitored species, not only because of its commercial value, but also because they are known to highly bioaccumulate pollutants. Examples are *Brosme Brosme* (tusk), *Coryphaenoides rupestris* (roundnose grenadier), *Glyptocephalus cynoglossus* (witch flounder), *Hippoglossoides platessoides* (American plaice), *Microstomus kitt* (lemon sole) or *Pleuronectes platessa* (European plaice). This type of species lives on the sediment layer at the sea bottom (benthic organisms), and directly uptake contaminants from sediment particles apart from diet (*26,27*). Pollutants tend to be associated with organic matter due to their lipophilic character (*3*), and at the same time, organic matter is bound to suspended particles in the water column that end up in the sediment layer (marine snow) (*28*). Moreover, deep water fish have a significant potential for the accumulation of POPs because many of the deep water species feed at higher trophic levels and live longer than pelagic fish (*29*).

2.2. Pollutant levels in discarded FAROS species

A review of studies presenting the quantitative pollutant contents in fish was developed. Values of either heavy metals and/or POPs (PCDD/Fs, PCBs and OCPs) in European commercial species are reported in Tables 1 and 2. These commercial species are considered as discards in Great Sole Bank and Atlantic Spanish and Portuguese coast métiers (although most of them usually at a very low rate) for different reasons. The main ones are: i) legal reasons related to the quota system; ii) strategic or commercial reasons; iii) lack of quality in the case of damaged specimens or in poor condition; etc (*25*).

Data were collected from market surveys in different countries and from other relevant studies available on commercial fish species (flesh or viscera). Origin was also included when possible. Although many studies on pollutant monitoring are available for the area of the Baltic Sea, they were not included in Tables 1 and 2 since the species monitored (herring, cod, sprat, etc.) are different from those considered in the selected fishing area (Great Sole Bank and coastal waters of the Atlantic side of the Iberian Peninsula). Pollutant concentration values for a total of 43 species were recorded, 14 of them corresponding to the most discarded species in the métiers considered in this analysis (marked on grey in Tables 1 and 2).

In Table 1, metal concentrations present in 30 fish species identified as target and main discarded on the Atlantic fisheries considered in FAROS framework are summarized. In general, a wide range of concentration values were found for all the metals considered. Zn, As and Cu reached the highest concentrations in the liver of *Aphanophus carbo*. This deep sea fish presented in most of occasions the highest concentrations for all metals.

Heavy metal bioaccumulation is related to biotic and abiotic factors such as water temperature, fish biological habitat, chemical form of metal in the water, fish species, gender and length or age (*50*). In general, it was observed that concentrations of metals are significantly higher in liver tissues than in muscle for the monitored species. This is particularly of concern when thinking in produce fish oil from livers. Concentration values ranges can vary widely among species and even for the same species in the same study, which implies a clear influence of location (as expected). Among the most-monitored species, specimens of *Aphanophus carbo* (black scabbard), *Coryphaenoides rupestris* (roundnose grenadier) and in less proportion *Merluccius merluccius* (hake), *Sardina pilchardus* (sardine) and *Scomber scombrus* (Atlantic mackerel) presented levels of pollution that can be of concern when thinking in further valorization technologies, since concentration steps are always present in these processes.

Concentrations of PCDD/Fs, PCBs, HCB, DDTs, chlordane, PBDEs, DDE and HBCD are shown in Table 2. PCBS and PCDD/Fs were the most frequently analyzed pollutant, due to their higher toxic effects on human health.

In many of the studies shown in Tables 1 and 2, the exposure to a variety of pollutants by fish ingestion was assessed (*6,7,41,42*). The conclusions were similar in most of them: moderate fish consumption not only does not pose a risk to human health but also has numerous nutritional benefits. However, production of fish oil and meal involves concentration processes that could increase pollutant concentration in valorized products, becoming an important problem.

3. Pollutant removal techniques

As previously mentioned, the most common uses of discards are the production of fish oil and meal. As shown in Table 3, pollutant concentration values available in the literature for fish oil and meal produced from species of different origin and location reveals that, in some cases, these levels can be of concern when compared to the limits established on the European Commission Directive 2006/13/EC on undesirable substances in animal feed as regards dioxins and dioxin-like PCBs (*18*). Therefore, purification step/s would be needed before consumption. In the next section, a revision of available decontamination techniques for fish valorized products (fish oil and meal) and other marine solid by-products is presented.

3.1. Fish oil

A key factor during fish oil refining is to remove contaminants without altering the levels of present nutritionally valuable compounds and the oxidative status of the oil (*54,55*). A reduction of some type of pollutants associated to fish oil during refining has been assessed. This is due to the fact that crude fish oils are usually refined to reduce the content of free fatty acids, metal traces, pigments, etc. In particular, the deodorization step (steam distillation at high temperature and vacuum) causes a decrease not only in residual pigments and other volatile compounds, but also the almost total removal of most volatile pollutants like organochlorine pesticides (α-HCH, lindane, etc) and the reduction to a half of the initial concentration of PCBs and less volatile organochlorine pesticides (*56*). However, standard conditions (180 ºC and 2 hours of contact) of deodorization are found to be inefficient for the removal of dioxins and furans.

Most up-to-date efficient removal methodologies for fish oil involve the use of a solid apolar adsorbent (like activated carbon), distillation processes, extraction processes or a combination of these techniques.

3.1.1. Extraction with solid adsorbents

Generally, purification of fish oil by solid adsorption is performed by mixing the oil with the adsorbent in a rotavapor under different experimental conditions, usually at mild pressure and temperature. The oil is subsequently separated from the adsorbent by filtration over a paper filter.

Eppe et al. (*57*) investigated oil purification by solid adsorbents for decreasing PCDD/Fs and dioxin-like (DL-) PCBs levels in order to be in compliance with European Legislation. The adsorbers tested were bleaching earths (polar adsorbents), acid activated silica powder, Dieatomecious earth, and several types of activated carbon (apolar adsorbents). Among the tested adsorbers, only activated carbon could significantly remove the PCDD/Fs (up to 99%) and DL-PCBs (up to 50%) concentration in cod liver oil. Optimum pressure and temperature of 0.05 bar and 74 ºC were established, respectively. Besides, it was concluded that reaction time within the range of 10 to 50 minutes had virtually no influence on the adsorption of pollutants, while the dose of activated carbon was the most influential variable, since the higher the dose, the higher the adsorption of contaminants.

A similar study was developed by Maes et al. (55), who evaluated the efficiency of different grades and doses (0.1 to 0.5% ww) of activated carbon to remove PCDD/Fs and DL-PCBs from cod liver oil. The process was performed at reduced pressure (0.05 bar) and moderate temperature (70 ºC) with a 30-minute reaction time. An almost complete elimination of PCDD/Fs and 80% removal of DL-PCBs were achieved with 0.5% of high-grade activated carbon. The lower PCBs removal was due to the minor adsorption of the mono-ortho fraction (30% or less), since their noncoplanar geometrical structure present low affinity to activated carbon.

Optimization of activated carbon adsorption for the reduction of POPs in commercial fish oil was performed by response surface methodology (*58*). PCDD/Fs were eliminated in a 99%, while non-ortho PCBs and mono-ortho PCBs were reduced to a maximum of 87 and 21%, respectively, operating at 80 ºC and 15 minutes of contact time. However, PBDEs reduction was not observed with this treatment. The authors stated that an increase in the adsorption temperature will probably enhance DL-PCBs reduction. However, they advise that it is necessary to have a compromise between optimal processing conditions, capacity utilisation, target Toxic Equivalent Quantity (TEQ) and oil quality specifications in large-scale industrial operations.

Usydus et al. (*59*) employed activated carbon at industrial scale to purify fish oil from different origins (sprat, herring and salmon). Optimum purification parameters were obtained in previous studies at laboratory scale (*60*), and were: dose of 1.2% weight, temperature of 85 ºC and 90 minutes of contact time. Although the oil loss produced during purification was approximately 20%, the removal of PCDD/Fs and dl-PCBs was 77.0-99.6% and 42.7-50.0%, respectively, depending on the raw material. These authors also evaluated the reduction of OCPs, PBDEs and Cd, Pb and Hg, which was negligible.

11 silicon-based and 9 carbon-based adsorbents were tested for the elimination of PCDD/Fs, PCBs, PBDEs, DDTs and HCBs from refined salmon oil by Ortiz et al. (*61*). Silicon-based adsorption was developed at 1.5% w/w, 50 ºC of temperature and atmospheric pressure, according to previous studies (*54*). However, silicon-based adsorbents and graphitized carbon were not suitable for the removal of POPs. On the contrary, activated carbon adsorbents showed a very high removal capacity for these pollutants. DL-PCBs were also better removed by activated than by graphitized carbon, although efficiency was lower than in the case of PCDD/Fs (18-24%). For the remaining POP evaluated, low effectiveness of both types of carbon-based adsorbent was observed, due to their non-planar structure. However, optimization of the adsorption process with coconut-shell activated carbon by response surface methodology resulted in an increase of the POP removal efficiencies. Operating at a

dose of 2.5% w/w during 37.5 minutes with a temperature of 80 ºC and 1 bar resulted in eliminations of 99% PCDD/Fs, 70% HCBs, 36% dioxin-like PCBs, 27% DDTs, 11% marker PCBs and 9% PBDEs.

In general, activated carbon adsorption is an appropriate method for removing dioxins and furans, but low elimination efficiencies are obtained for DL-PCBs. Efficient activated carbon adsorption depends on a planar molecular conformation, and this will strongly limit the number of possible POP to remove based on this technology (*58*). Therefore, complete decontamination of fish oil could only be achieved by a combination of activated carbon with other extraction (stripping) process (*55,62*).

3.1.2. Supercritical CO_2 extraction

Supercritical CO_2 extraction (SCE) has been applied to several different processes, like selective extraction of valuable natural products, separation of contaminants and other processes because of its extraction selectivity, low critical point and lack of flammability, toxicity and corrosiveness (*17*). SCE for removal of pollutants from fish oil has been performed in semi-batch and counter current installations. One of the first attempts of investigating the feasibility of supercritical counter current fluid extraction for pollutant removal in fish oil was the study conducted by Krukonis (*63*). The author found that PCBs can be extracted from cod oil with supercritical carbon dioxide at quite modest temperature and pressure, with little yield loss of the fish oil. During the experiment, temperature was held constant at 70 ºC and pressure was gradually increased from 172.4 to 448.2 bar. However, it was stated that subsequent increases from 241.3 bar did not increase the extractability of the pollutants. Although the results obtained in this lab-scale study were promising, it was advised to subject the process to a detailed economic viability evaluation, as well as to analyze factors such as stability to autoxidation during storage and product performance.

Some years later, Jakobsson et al. (*64*) investigated the elimination of dioxins and dibenzofurans from cod liver oil. The main objective or their study was to test the counter current method and to establish the influence of the feed oil/CO_2 ratio on the extractability of these compounds from the fish oil. The results obtained showed that the higher the carbon dioxide/oil ratio, the smaller the recovery of oil. The most effective extraction (80% of dioxins together with 17% of the oil) was achieved at ratios of 100. However, improvements in this technique have led to a consequent increase in pollutant removal efficiencies and to a decrease in oil loss.

Kawashima et al. (*62*) investigated the removal of PCDD/Fs and coplanar PCBs from menhaden oil by SCE and by activated carbon adsorption. Experimental conditions of SCE were 60 ºC of temperature, 280 bar of pressure and a CO_2 flow volume of 50 L/g oil. This method proved effective to remove PCBs, with elimination percentages ranging from 70% to 90%. However, removal efficiency decreases as the molecular weight of PCDD and PCDF congener increases, being in the range of 15-90% depending on the molecule. For the effective removal of high-chlorinated PCDD/Fs, the authors considered an adsorption process with activated carbon. Removal ratios of this process were higher than 90% for all of the isomers of PCDD/Fs, while removal percentages for PCBs were within 1% (mono-ortho) and 30% (non-ortho). Consequently, a combined removal process (SCE with CO_2 followed by activated carbon adsorption) was more effective, since almost 100% of the total TEQ value was reduced.

The same authors advanced in this field, assessing the use of continuous counter current supercritical CO_2 extraction and activated carbon adsorption for removing pollutants from fish oil (*17*). In their previous work (*62*), SCE was found to have high efficiency in DL-PCBs removal. However, semi-batch processes require long operation times, producing a purified oil yield not enough for practical use. Thus, extraction conditions and contaminant removal efficiency of counter current SCE was investigated. As in Kawashima et al. (*62*), removal efficiencies decrease with an increase in the molecular weights of pollutants. Process efficiency also increased with extraction pressure, being the optimal operating conditions 300 bar of pressure, 70 ºC and a CO_2/oil ratio of 72. These conditions proved effective for the remove of DL-PCBs (93%) and PCDD/Fs congeners that have molecular weights less than 400. Fish oil refined by counter current SCE was subsequently treated with activated carbon for the elimination of PCDD/Fs, reaching values higher than 80% for each congener. Thus, the combined process reduces the pollutant concentration by 94%, while presenting a minimal influence on the fatty acid content of the oil. When compared with the semi-batch type process, counter current SCE uses 40% less CO_2 and yields 30% more refined oil. However, it is necessary to consider that fish oils extracted with CO_2 can lose much of its unsaturation during storage and can polymerize (*63*).

3.1.3. Short-path distillation

Short-path distillation (SPD) technology is characterized by operation with short residence times and high vacuum level. Breivik & Thorstad (*21*) presented an improved method based on this technology to eliminate POPs from marine oils. They found that with the addition of 3-6% of an ester mixture (working fluid) prior to the distillation, pollutants are removed in a much more efficient manner. In this case, the working fluid was a light ethyl ester fraction of transesterified fish oil produced as a by-product from commercial production of omega-3 concentrates. With this technique, concentration of dioxins and PCBs were reduced by more than 90%, including DL-PCBs. Moreover, DDT, toxaphene and PBRDs were removed to a level below the analytical detection limit.

Decontamination of sprat oil by SPD technology was evaluated by Oterhals et al. (*65*). The objective was to quantify the effect of evaporator temperature, feed rate and addition of a working fluid (*21*) on the reduction of PCDD/Fs, DL-PCBs and PBDEs. Furthermore, a model of SPD based on process parameters and quantitative structure properties relationship was proposed by the authors to relate removal efficiency with congener volatility. The results obtained in this study indicated that is not possible to define optimum operation conditions for POP reduction in fish oil by SPD due to the large variance in vapor pressures for the multicomponent mixture of organic compounds. However, as TEQ reduction is mainly influenced by the removal of PCDD/Fs and DL-PCBs, the best decontamination effect was obtained with a combination of low feed rate and high evaporator temperature and working fluid conditions.

The feedstock used in the study by Oterhals et al. (*65*) was the same as earlier reported on activated carbon-based decontamination of fish oil (*58*). Therefore, these authors were able to compare both removal methods. Activated carbon is an appropriate method for removing compounds like PCDD/Fs, PAHs and some congeners of PCBs, which present a coplanar structure, since effective adsorption is dependent on dispersive electronic interactions affected by sorbate planarity and steric effects (*66*). However, compounds like most of organochlorine pesticides and PBDEs are not adsorbed and removed by this method. On the contrary, the efficiency of a SPD based decontamination process is mainly dependent on the volatility of the respective compounds and the selection of favorable process conditions. SPD is less influenced by the conformation and chemical nature of POPs to be removed when compared to activated carbon adsorption (*65*).

However, the use of SPD to eliminate POPs from fish oils will also remove other volatile compounds and decrease the nutritional value and oxidative stability of the oil. This fact is due to the high temperature levels (>200 ºC) applied to the fish oil during the process. Oterhals and Berntssen (*67*) quantified the effects of alternative SPD process conditions on the oil nutritional and oxidative properties and identified the optimal process conditions by combining decontamination effects in compliance with legislation levels and maximum retention of nutritional quality. Some reduction in the oxidation level was observed, but with preservation of PUFA level and quality. Only 76% of reduction of the TEQ level was achieved in the fish oil to be in accordance with international quality standards, with a final loss of vitamins lower than 20%. If a higher decontamination level is required (90%), vitamin retentions can vary between 60-90%.

3.1.4. Other procedures

Other volatilization procedures (steam deodorization) were tested to eliminate POPs from fish oils. Carbonelle et al. (*68*) used a combination of an activated carbon adsorption treatment with either packed column stripping or cross-flow stripping. The last two methods were introduced with the aim of improving the removal of mono-ortho PCBs, since activated carbon is not adequate for this task. Packed column and cross-flow stripping are procedures that involve high temperature, low pressure and injection of a stripping agent (steam). Differences between them are residence time (very short in packed column), pressure (pressure drop in packed column and constant in cross-flow) and contact between oil and steam (counter-current in packed column). The authors decided to combine cross-flow stripping (instead of packed column) with activated carbon because this technique is preferable in an industrial process. With an optimum combination of these methods, removal of 100% of dioxins and furans, more than 95% of non-ortho PCBs and between 48 and 74% of mono-ortho PCBs was achieved. However, the final nutritional quality (PUFA content, etc) of the product was not evaluated.

3.2. Fishmeal and other marine solid wastes

Although several alternatives have been tested for the elimination of pollutants from fish oil, less emphasis has been given to the development of purification alternatives for fishmeal and marine solid by-products/wastes without decreasing its nutritional/reusable value. Regarding fishmeal, decontamination techniques like ultraviolet (UV) light, extraction with either organic solvents or oil, and enzymatic treatments have been evaluated.

Baron et al. (*69*) applied UV on contaminated fishmeal to photodegrade dioxins. After 5 days of exposure to UVB light, degradation of 70% of PCDD/Fs content was obtained. However, the photodegradation mechanism triggered lipid oxidation and increase the content of non- and non-ortho PCBs as reaction products in the treated fishmeal. This fact, linked to the high exposure time required, make the application of this methodology at industrial scale unfeasible. Although an increase in the light intensity should decrease exposure time, oxidation of long-chain fatty acids would also be enhanced. The authors proposed the addition of antioxidants to avoid this undesirable process.

As previously mentioned, persistent organic pollutants are lipophilic compounds, and the reduction of the fat content in fishmeal will result in the concurrent reduction of these undesirable compounds. Baron et al. (*70*) studied several techniques to remove dioxin and DL-PCBs from fishmeal. The studied methods were fat extraction with organic solvents, oil, protease and direct breakdown of dioxin and PCBs using oxidoreductase. Low reduction of pollutant content was observed with fat separation after protease treatment (30%) and with PCDD/Fs and DL-PCBs degradation by oxidoreductase (10-15%). The organic solvents (ethanol, isopropanol and isohexane) reduce the fat content to 80%, with a proportional reduction of pollutants, but the fishmeal had a low nutritional quality and might content traces of solvents. Extraction of dioxin and PCBs using olive oil or fish oil resulted in 60%-75% of decontamination effect. Enrichment of the oily phase in pollutants was observed for all congeners and both oil types. Increasing the time of extraction (24 hours) only resulted in a minor increase in the levels of POPs in oils, indicating that equilibrium and partitioning of the contaminant into the oil is a fast process (*70*). Oterhals and Nygard (*71*) also investigated the reduction of persistent organic pollutants in fishmeal at pilot scale by organic solvent and soybean oil extraction. Both extraction agents provided fishmeal products with a TEQ value below the maximum permitted levels. However, lowest levels were observed with soybean oil (reduction of 97% of TEQ). Moreover, the estimated fat content of the extracted product presented a value close to the respective one in ordinary processed fishmeal. This was considered as a critical success factor if the process should be used in industrial application. The obtained decontamination rates in this work were higher than those reported by Baron et al. (*70*) on the basis of olive oil extraction. According to Oterhals and Nygard (*71*), the difference might be explained by the combined use of a higher extraction temperature (88 ºC vs room temperature) and oil/matrix ratio (1:3 vs 1:1). From the industrial point of view, the oil extraction process has several advantages when compared to organic solvent extraction, like for example, easy integration in an existing fishmeal processing line and the use of a safe and non-flammable extraction medium.

Other type of pollutants found in marine solid by-products are metals. Removal of these compounds from the solid matrix is critical for its subsequent reuse and valorization as fodder. Tavakoli and Yoshida (*72*) investigated the use of sub- and supercritical water treatment as a method for recovering heavy metals from squid wastes. Reaction temperature ranged between 443 and 653 K and the pressure range between 7.92-300 bar, and produced four phases (unreacted solid, aqueous, fat and oil). Distribution coefficients of the metals considered (Cd, Cu and Zn) followed the decreasing order fat>solid>oil>aqueous phase. The proposed decontamination waste process is energy efficient according to the authors, and produces valuable products (oil, soluble proteins, organic acids and aminoacids) from waste. In addition, metal ions can be recovered from waste streams and recycled back to the related industries. Other techniques for the removal of metals from marine by-products involve a coagulation process. Ghimire et al. (*73*) proposed an environmental friendly removal process of heavy metals from Cd-contaminated scallop waste by using apple waste and astringent persimmon extract (kaki-shibu), which has the advantage of a coagulating effect independent of pH. The process consists of three steps: 1) leaching of all metals contained in scallop waste by dilute sulphuric acid; 2) removal by kaki-shibu coagulation of turbid organic materials from the leach liquor and; 3) adsorption of heavy metals onto a gel prepared with apple waste. To adjust pH (lower in the leaching process and higher during the adsorption), the authors proposed a counter current process, recycling the leach liquor to the feed waste. The obtained cadmium free scallop waste can be used as cattle and fish fodder, while the cadmium free apple waste can be reused as fertilizer.

Discards are one of the most important topics in fisheries, both from an economic and environmental point of view. The contribution to a sustainable management of this biomass through their optimal valorization highly depends on the quality of the products to be obtained from them. The products of discard valorization are mainly concentrates, being the most common ones fish oil and meal. Pollutants contained in the raw material are usually present at higher concentrations in the valorized product, especially if the product has a high fat content (oil). Therefore, reduction and/or elimination of undesirable and toxic compounds from fish oil and fishmeal is a key factor for its safe reuse, either as feed in aquaculture or as additive in food products.

Three techniques are currently available to reduce POPs from fish oil: 1) solid adsorbers (activated carbon), 2) SCE and, 3) SPD. Although SPD remove a wider variety of pollutants (PCDD/Fs, DL-PCBs, PBDEs, OCPs) than SCE or activated carbon adsorption, this technique is performed under experimental conditions (especially of temperature) that can affect the positive properties of the oil if a high degree of decontamination is needed. SCE has a minimal environmental impact and preserve the PUFA content of the treated oil, although some authors found unstable behavior of the oil during storage. However, it is not efficient for the removal of high-chlorinated PCDD/Fs, and for that reason, can be combined with activated carbon adsorption, that effectively removes dioxins and furans. The selection of the most appropriate technique for oil decontamination mainly depends on the pollutant type and congener found in the oil, and the percentage of TEQ value reduction needed to comply with legislation, which is different according to the final use (feed or food). Regarding fishmeal, the most effective method to remove pollutants is the reduction of the fat content. Extraction or separation of fat content can be achieved by extraction with organic solvent and oil, or with enzymatic treatment. The most promising method so far is the extraction with oil (olive, soybean, etc.), which does not alter the nutritional properties of the meal and does not involve the use of toxic solvent. For metal elimination, critical extraction or coagulation methods can be used.

As stated, the assessment of pollution levels in fish and the application of removal techniques when necessary is a key factor for an effective discards management. Nonetheless, more alternatives apart from fish oil and meal must be provided to the processing sector in order to optimize the reuse of the different species by the production of high-added value products. Hence, valorizing potential of the most discarded species in FAROS project will be evaluated in the second part of this work. The potential presence of contaminants will be discussed in terms of valorization process of the different species.

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Supporting Information Available

Availability of pollutant monitoring data for discarded species in Spanish and Portuguese fisheries is shown in Table S1.

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Table S1. Presence of Different Pollutants in Discarded Species of Spanish and Portuguese *Métiers*

Specie	Pollutant profile
Actinauge richardi	No data available
Alosa alosa	-
Alosa fallax	-
Alepocephalus rostratus	No data available
Aphanopus carbo	Heavy metals (Al, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, V and Zn)
Argentina silus	-
Argentina sphyraena	-
Argobuccinum olearium	No data available
Arnoglossus imperialis	-
Arnoglossus laterna	-
Aspitrigla cuculus	-
Asteroidea	No data available
Beryx decadactylus	-
Boops boops	-
Brama brama	-
Brosme brosme	PCBs, α-HCH, DDE, DDT, γ-HCH, HCB, octachlorostyrene, pentachlorobenzene, DDD and heavy metals (Cd, Cu, Pb, Hg and Zn)
Buccinum spp.	No data available
Caelorinchus caelorhincus	-
Callionymus lyra	-
Callionymus reticulatus	-
Cancer bellianus	No data available
Cancer pagurus	-
Capros aper	-
Cassidaria tyrrhena	No data available
Centrolophus niger	No data available
Centrophorus granulosus	No data available
Centrophorus squamosus	No data available
Centroscymnus coelolepis	No data available
Centrostephanus longispinus	No data available
Cepola macrophthalma	No data available
Charonia lampas	No data available
Chelidonichthys cuculus	-
Chelidonichthys gurnardus	No data available
Chelidonichthys lucerna	No data available
Chimaera monstrosa	PCBs, α-HCH, DDE, DDT, γ-HCH, HCB, octachlorostyrene, pentachlorobenzene, DDD and heavy metals (Cd, Cu, Pb, Hg and Zn)
Caelorinchus caelorhincus	-
Conger conger	-
Coryphaenoides rupestris	Heavy metals (Al, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, V and Zn)
Crinoidea	No data available
Crustacea	-
Dalatias licha	No data available
Dardanus arrosor	No data available
Deania calcea	No data available
Dipturus batis	-
Echinoidea	No data available
Echinodermata	-
Echinus acutus	No data available
Eledone cirrhosa	-
Etmopterus spinax	-
Eutrigla gurnardus	-
Gadiculus argenteus	-
Gadus morhua	Dioxins, furans, benzenes, bromocyclododecane, naphthalenes, PCBs, PAHs, alpha-endosulfan, α-HCH, α-HBCD, β-endosulfan, β-HCH, β-HBCD, dibenzothiophenes, cesium-134, cesium-137, cis-chlordane, cis-nonachlor, DDE, DDT, PBDEs, dibutyltin, dieldrin, endrin, γ-HCH, γ-HBCD, heptachlor, heptachlor epoxide, HCB, hexachlorobutadiene, methoxychlor, mirex, monobutyltin, monophenyltin, PBTs, oxychlordane, toxaphene, pentachlorothioanisole, perfluorodecanoic acid, perfluoroheptanoic acid, perfluorohexanesulfonic acid, perfluorohexanoic acid, perfluorononanoic acid, perfluorooctanoic acid, perfluorooctanyl sulphonic acid, perfluorooctylsulfonate acid amide, perylene, radium-226, radium-228, N, P, DDD, tetrabromobiphenol, trans-chlordane, trans-nonachlor, tributyltin, triphenyltin and heavy metals (As, Cd, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Hg, Na, Ni, K, Se, Sn and Zn)
Gaidropsarus guttatus	No data available
Galeorhinus galeus	-
Galeus melastomus	-
Gastropoda	-
Geryon longipes	No data available
Glyptocephalus cynoglossus	PCBs, α-HCH, DDE, γ-HCH, HCB, octachlorostyrene, pentachlorobenzene, DDD and heavy metals (Cd, Cu, Pb, Hg and Zn)
Gobiidae	-
Halargyreus johnsonii	No data available
Helicolenus dactylopterus	-

Hexanchus griseus	-
Hippoglossoides platessoides	PCBs, α-HCH, β-HCH, cis-chlordane, DDE, DDT, γ-HCH, HCB, oxychlordane, DDD, trans-chlordane, trans-nonachlor and heavy metals (As, Cd, Cr, Cu, Pb, Hg, Ni, Se and Zn)
Holothuria spp.	No data available
Holothurioidea	No data available
Hoplostethus atlanticus	Heavy metals (Al, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, V and Zn)
Hoplostethus mediterraneus	No data available
Illex coindetii	-
Lepidion eques	-
Lepidopus caudatus	-
Lepidorhombus boscii	-
Lepidorhombus spp.	No data available
Lepidorhombus whiffiagonis	PCBs, α-HCH, cis-chlordane, DDE, DDT, dieldrin, γ-HCH, HCB, octachlorostyrene, pentachlorobenzene, DDD, trans-chlordane, trans-nonachlor and heavy metals (As, Cd, Cr, Co, Cu, Pb, Hg, Ni, Ag, Sn and Zn)
Leucoraja circularis	-
Leucoraja naevus	-
Liocarcinus depurator	No data available
Loligo vulgaris	-
Lophius budegassa	-
Lophius piscatorius	PCBs, α-HCH, cis-chlordane, DDE, DDT, dieldrin, γ-HCH, HCB, DDD, trans-chlordane, trans-nonachlor and heavy metals (Al, Cd, Cr, Co, Cu, Fe, Pb, Li, Mn, Hg, Ni, Se, V and Zn)
Lophius spp.	-
Macropipus tuberculatus	-
Macropodia tenuirrostris longipes	No data available
Macroramphosus scolopax	-
Malacocephalus laevis	-
Melanogrammus aeglefinus	PCBs, PAHs, α-HCH, dibenzothiophenes, naphthalenes, cis-chlordane, DDE, DDT, dieldrin, γ-HCH, HCB, oxychlordane, perylene, DDD, trans-chlordane, trans-nonachlor and heavy metals (Cd, Cu, Pb, Hg and Zn)
Merlangius merlangus	PCBs, PAHs, α-HCH, dibenzothiophenes, naphthalenes, cis-chlordane, DDE, DDT, γ-HCH, HCB, perylene, DDD, trans-chlordane, trans-nonachlor and heavy metals (As, Cd, Cu, Pb, Hg and Zn)
Merluccius merluccius	PCBs, α-HCH, β-HCH, cis-chlordane, DDE, DDT, dieldrin, γ-HCH, HCB, DDD, trans-chlordane, trans-nonachlor and heavy metals (Cd, Cr, Cu, Pb, Hg and Zn)
Microchirus variegatus	-
Micromesistius poutassou	Heavy metals (Cd, Co, Cu, Pb, Li, Hg, Ni, Se, V and Zn)
Microstomus kitt	α-HCH, PCBs, dibenzothiophenes, naphthalenes, chrysene, cis-chlordane, DDE, DDT, dieldrin, γ-HCH, chlorobenzenes, octachlorostyrene, perylene, DDD, trans-chlordane, trans-nonachlor and heavy metals (Cd, Cu, Pb, Hg and Zn)
Mola mola	-
Mollusca	No data available
Molpadiidae	No data available
Molva dypterygia	Heavy metals (Al, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Ni, Se and Zn)
Molva molva	PCBs, α-HCH, γ-HCH, DDE, DDT, benzenes, octachlorostyrene, DDD and heavy metals (Cd, Cu, Pb, Hg and Zn)
Mora moro	-
Munida spp.	No data available
Mustelus asterias	-
Nephrops norvegicus	Naphthalenes, PCBs, PAHs, dibenzothiophenes, naphthalene, perylene and heavy metals (Cd, Cu, Pb, Hg and Zn)
Nettastoma melanurum	No data available
Nezumia aequalis	No data available
Nezumia sclerorhynchus	No data available
Octopodidae	-
Ommastrephidae	-
Opisthoteuthis agassici	No data available
Ophiothrix fragilis	-
Ophiura spp.	-
Pagellus acarne	-
Pagellus bogaraveo	-
Pagurus alatus	No data available
Pagurus spp.	No data available
Parapenaeus longirostris	No data available
Paromola cuvieri	No data available
Phycis blennoides	-
Phycis spp.	No data available
Pisces	No data available
Plesionika spp.	No data available
Pleuronectes platessa	PAHs, naphthalenes, PCBs, α-HCH, cis-chlordane, DDE, DDT, δ-HCH, γ-HCH, dieldrin, benzenes, perylenes,DDD, trans-chlordane, trans-nonachlor and heavy metals (As, Ba, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Se, Ag, Sr, Sn, V and Zn)
Pollachius virens	DDE, DDT, γ-HCH, HCB, PCBs and heavy metals (Cd, Cu, Pb, Hg and Zn)
Polybius henslowi	No data available
Polychaeta	-
Raja asterias	No data available
Raja brachyuran	No data available
Raja clavata	Hg

Raja montagui	Hg
Rajidae	No data available
Rhizopoda	No data available
Rossia macrosoma	-
Sacoglossa	No data available
Sardina pilchardus	PCBs and heavy metals (Cd, Cu, Pb, Hg and Zn)
Scaphander lignarius	No data available
Scomber colias	No data available
Scomber scombrus	PCBs, α-HCH, cris-chlordane, DDE, DDT, dieldrin, γ-HCH, HCB, DDD, trans-chlordane, trans-nonachlor and heavy metals (Cd, Cr, Cu, Pb, Hg and Zn)
Scyliorhinus canicula	Hg
Scymnodon ringens	No data available
Scyphozoa	-
Sepia officinalis	-
Sepia orbignyana	-
Sepia spp.	-
Sepiola spp.	-
Squalus acanthias	-
Sphoeroides pachygaster	No data available
Stichopus spp.	No data available
Stichopus tremulus	No data available
Tealia spp.	No data available
Todarodes sagittatus	No data available
Todaropsis eblanae	-
Torpedo marmorata	-
Trachurus mediterraneus	No data available
Trachurus picturatus	No data available
Trachurus spp.	No data available
Trachurus trachurus	-
Trachyrincus scabrus	No data available
Trigla lyra	-
Trigla spp.	No data available
Triglidae	No data available
Trisopterus luscus	-
Trisopterus minutus	-
Zeus faber	-

Table 1. Metal Levels in Atlantic Fish Species

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww)	Reference
Aphanopus carbo				
(black scabbardfish)				
West Scotland	muscle	As	<0.002-26.49	(30)
		Cd	<0.002-0.017	
		Cu	0.07-0.27	
		Pb	0.002-0.052	
		Zn	2.12-3.90	
	liver	As	<0.05-35.79	
		Cd	2.06-18.24	
		Cu	<1.00-39.05	
		Pb	<0.05-0.471	
		Zn	29.42-108.70	
Madeira and Azores	muscle	Hg	0.19-1.43	(31)
		Cd	0.01-0.09	
		Pb	nd-0.10	
	liver	Hg	0.28-1.19	
	skin	Hg	0.04-1.44	
		Cd	0.02-0.11	
		Pb	nd-0.10	
Brosme brosme				
(tusk or cusk)				
Northeast Atlantic		Zn	3.0-3.5	(32)
		Cu	0.13-0.18	
Chelidonichthys gurnardus				
(grey gurnard)				
Northeast Atlantic		Zn	3.0-4.2	(32)
		Cu	0.23-0.39	
Conger conger				
(European conger)				
Croatia		Hg	0.864	(7)
Coryphaneoides rupestris				
(roundnose grenadier)				
West Scotland		Cd	ND-0.01	(33)
		Cu	0.03-0.54	
		Pb	ND-0.06	
		Hg	0.02-0.28	
		Zn	1.7-2.9	
Helicolenus dactylopterus				
(blackbelly rosefish)				
Portuguese coast		Cr	0.23-0.28	[1](34)
		Ni	0.038-0.065	

Specie, origin and tissue (muscle when not specified)	Pollutant	Concentration (mg/kg ww)	Reference
	Hg	0.44-1.35	
	Pb	ND	
	Cd	0.025-0.013	
Hippoglossoides platessoides			
(American plaice)			
Barents Sea liver	Cd	0.4	[1](35)
	Hg	0.018	
	Cu	8.0	
	Zn	29.75	
muscle	Hg	0.093	
	Cu	<0.43	
	Zn	4.75	
Hoplostethus atlanticus			
(orange roughy)			
West Scotland	Cd	ND-0.01	(33)
	Cu	0.04-0.19	
	Pb	ND-0.66	
	Hg	0.11-0.86	
	Zn	2.0-3.4	
Lepidorhombus boscii			
(four-spot megrim)			
Northern Iberian shelf-liver	Cu	2.45-6.93	[1](36)
	Zn	19.5-40.75	
	Cr	0.25-0.72	
	Fe	25.25-55.5	
	Cd	0.025-0.34	
	Pb	0.0005-0.0028	
	Hg	0.0028-0.11	
Lepidorhombus whiffiagonis			
(megrim)			
Northeast Atlantic	Zn	2.1-2.9	(32)
	Cu	0.13-0.47	
Loligo vulgaris			
(European squid)			
Catalonian markets	As	1.41-4.74	(6)
	Cd	0.05-0.15	
	Hg	0.02-0.03	
	Pb	0.01-0.01	
France	Hg	0.047	(7)
Lophius piscatorus			
(monkfish)			
West Scotland muscle	As	2.70-21.47	(30)
	Cd	<0.002-0.041	

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww)	Reference
		Cu	0.06-0.22	
		Pb	<0.002-0.041	
	liver	As	1.44-14.33	
		Cd	<0.05-1.4	
		Cu	1.45-36.44	
		Pb	<0.05-0.074	
Northeast Atlantic		Zn	2.6-3.3	(32)
		Cu	0.10-0.29	
Portuguese coast		Cr	0.0075-0.53	(34)
		Ni	0.02-0.053	
		Hg	0.118-0.63	
		Pb	<0.0075	
		Cd	0.0025-0.0075	
Croatia		Hg	0.071–0.678	(7)
Melanogrammus aeglefinus (haddock)				
Barents Sea	liver	Cd	0.35	[1](35)
		Hg	0.013	
		Cu	6.75	
		Zn	14	
	muscle	Hg	0.083	
		Cu	<0.43	
		Zn	3.75	
Northeast Atlantic		Zn	2.2-4.0	(32)
		Cu	0.13-0.34	
Merluccius merluccius (hake)				
West Scotland	muscle	As	0.08–3.30	(30)
		Cd	<0.002–0.062	
		Cu	0.16–0.54	
		Pb	<0.002–0.047	
	liver	As	<0.05-7.59	
		Cd	<0.05-1.43	
		Cu	<1.00-17.89	
		Pb	<0.05-0.159	
Northeast Atlantic		Zn	3.2-3.3	(32)
		Cu	0.20-0.61	
Catalonian markets		As	3.22-4.55	(6)
		Cd	0.005-0.01	
		Hg	0.12-0.29	
		Pb	0.01-0.13	
Croatia		Hg	0.052	(7)
Micromesistius poutassou				

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww)	Reference
(blue whiting)				
West Scotland	muscle	As	0.37–6.10	(30)
		Cd	<0.002–1.178	
		Cu	0.19–0.45	
		Pb	0.005–0.030	
	liver	As	1.52-13.74	
		Cd	0.06-1.29	
		Cu	2.56-10.18	
		Pb	<0.05-0.061	
Microstomus kitt				
(lemon sole)				
Northeast Atlantic		Zn	2.6-2.9	(32)
		Cu	0.19-0.38	
Molva dypterygia				
(blue ling)				
West Scotland	muscle	As	1.84-13.09	(30)
		Cd	<0.002–0.004	
		Cu	0.10–0.41	
		Pb	<0.002–0.008	
	liver	As	<0.02-32.44	
		Cd	<0.55-1.59	
		Cu	<1.00-7.10	
		Pb	<0.05-0.336	
Molva molva				
(ling)				
Northeast Atlantic		Zn	2.7-3.6	(32)
		Cu	0.13-0.22	
Pagellus acarne				
(axillary seabream)				
Portuguese coast		Cr	0.15-0.425	[1](34)
		Ni	0.023-0.063	
		Hg	0.22-0.96	
		Pb	0.0025-0.018	
		Cd	0.0025-0.01	
Pagellus bogaraveo				
(black spot or red seabream)				
Portuguese coast		Cr	0.15-0.43	[1](34)
		Ni	0.023-0.063	
		Hg	0.22-0.96	
		Pb	0.0025-0.018	
		Cd	0.0025-0.01	
Phycis phycis				
(forkbeard)				

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww)	Reference
Portuguese coast		Cr	0.18-0.325	[1](34)
		Ni	0.02-0.035	
		Hg	0.14-0.59	
		Pb	<0.008	
		Cd	0.0025-0.013	
Pleuronectes platessa (European plaice)				
Barents Sea	liver	Cd	0.53	[1](35)
		Hg	0.045	
		Cu	3	
		Zn	26.3	
	muscle	Hg	0.06	
		Cu	0.68	
		Zn	5.75	
Pollachius virens (saithe)				
Barents Sea	liver	Cd	0.058	[1](35)
		Hg	0.005	
		Cu	1.75	
		Zn	9.75	
	muscle	Hg	0.08	
		Zn	7.0	
Northeast Atlantic		Zn	3.7-4.5	(32)
		Cu	0.46-0.65	
Sardina pilchardus (sardine)				
Catalonian markets		As	3.53-3.94	(6)
		Cd	0.002-0.01	
		Hg	0.07-0.09	
		Pb	0.01-0.08	
Spanish market		Hg (total)	0.06	(37)
Portuguese waters and markets		Hg	0.0116–0.0280	(8)
		Cd	0.0017–0.0151	
		Pb	0.0029–0.0569	
		As	0.8116–1.336	
Scomber scombrus (Atlantic mackerel)				
Northeast Atlantic		Zn	3.3-5.2	(32)
		Cu	0.70-0.97	
Catalonian markets		As	1.73-7.47	(6)
		Cd	0.003-0.01	
		Hg	0.06-0.15	
		Pb	0.01-0.02	

Specie, origin and tissue (muscle when not specified)	Pollutant	Concentration (mg/kg ww)	Reference
Slovenia	Hg	0.035-0.056	(7)
Scyliorhinus caniculus			
(small-spotted catshark)			
Northeast Atlantic	Zn	8.5-8.7	(32)
	Cu	0.50-0.53	
Sepia spp			
(cuttlefish)			
Catalonian markets	As	2.45-5.33	(6)
	Cd	0.01-0.09	
	Hg	0.04-0.08	
	Pb	0.01-0.10	
Trachurus trachurus			
(Atlantic horse mackerel)			
Mauritania	Cd	0.01	[1](38)
	Cu	0.4	
	Zn	10.5	
	Hg	0.075	
Portuguese waters and markets	Hg	0.0380–0.3371	(8)
	Cd	0.0030–0.0141	
	Pb	0.0031–0.0215	
	As	0.655–1.941	
Trisopterus luscus			
(pouting)			
Northern Iberian shelf-liver	Cu	0.58-2.0	[1](36)
	Zn	2.0-6.25	
	Cr	0.11-0.89	
	Fe	17.0-29.5	
	Cd	0.005-0.085	
	Pb	0.0005-0.013	
	Hg	0.00025-0.0085	
Zeus faber			
(John dory)			
Northeast Atlantic	Zn	3.1	(32)
	Cu	0.12-0.14	
Morocco	Hg	0.066	(7)

[1] assuming wet/dry ratio of 0.25

Table 2. POPs Levels in Atlantic Fish Species

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww for metals and µg/kg ww for POPs)	Reference
Aphanopus carbo				
(black scabbardfish)				
West Scotland	muscle	PBDE	0.194-0.98	(29)
	liver	PBDE	0.57-11.98	
Ireland-liver		HCB	3.89	(39)
		PCBs	17.03	
		DDTs	75.64	
		chlordane	22.8	
Madeira-liver		HCB	0.43	(39)
		PCBs	112.34	
		DDTs	107.42	
		chlordane	15.83	
Meriadzec-liver		HCB	2.13	(39)
		PCBs	93.8	
		DDTs	185.6	
		chlordane	49.1	
Rockall-liver		HCB	2.62	(39)
		PCBs	15.9	
		DDTs	43.8	
		chlordane	12.6	
Sesimbra-liver		HCB	3.2	(39)
		PCBs	257.2	
		DDTs	165.4	
		chlordane	30.7	
Arnoglossus laterna				
(Mediterranean scaldfish)				
Adriatic Sea		PCBs	2.07	(40)
Southern Mediterranean		dl-PCBs	0.23	(41)
Adriatic Sea		PCBs	2.13	(42)
		PCDD/Fs	ND	
Aspitrigla cuculus				
(red gurnard)				
Adriatic Sea		PCBs	1.08	(40)
Adriatic Sea		PCBs	1.06	(42)
		PCDD/Fs	0.00022	
Boops boops				
(bogue)				
Adriatic Sea		PCBs	3.13	(42)
		PCDD/Fs	0.00024	
Brosme brosme				
(tusk or cusk)				

Specie, origin and tissue (muscle when not specified)		Pollutant	Concentration (mg/kg ww for metals and µg/kg ww for POPs)	Reference
Cancer pagurus				
(edible crab)				
South Norway	hepatopancreas	PCDD/Fs	0.639-15.98	(11)
	claw meat	PCDD/Fs	0.125	
Conger conger				
(European conger)				
Adriatic Sea		PCBs	27.72	(42)
		PCDD/Fs	0.00026	
Croatia		PCBs	3.82	(7)
Coryphaneoides rupestris				
(roundnose grenadier)				
Ireland-liver		HCB	17.9	(39)
		PCBs	379.8	
		DDTs	577.7	
		chlordane	36.55	
West Scotland	muscle	PBDE	<dl-2.11	(29)
	liver	PBDE	2.08-91.9	
Eutrigla gurnardus				
(grey gurnard)				
Adriatic Sea		PCBs	2.08	(40)
Helicolenus dactylopterus				
(blackbelly rosefish)				
Adriatic Sea		PCBs	2.64	(42)
		PCDD/Fs	0.0002	
Hippoglossoides platessoides				
(American plaice)				
Northwest Atlantic		PBDE	0.62	(43)
Hoplostethus atlanticus				
(orange roughy)				
Meriadzec-liver		HCB	5.49	(39)
		PCBs	198.6	
		DDTs	151.4	
		chlordane	18.7	
Ireland-liver		HCB	9.95	(39)
		PCBs	260.76	
		DDTs	259.3	
		chlordane	38.64	
Lepidopus caudatus				
(silver scabbardfish)				
Adriatic Sea		dl-PCBs	1.10	(41)
Lepidorhombus boscii				
(four-spot megrim)				
Adriatic Sea		PCBs	0.657	(42)

Specie, origin and tissue (muscle when not specified)	Pollutant	Concentration (mg/kg ww for metals and µg/kg ww for POPs)	Reference
	PCDD/Fs	ND	
Lepidorhombus whiffiagonis (megrim)			
Adriatic Sea	PCBs	2.08	(40)
Loligo vulgaris (European squid)			
Lophius budegassa (blackbellied angler)			
Adriatic Sea	PCBs	0.245	(42)
	PCDD/Fs	0.0000056	
Lophius piscatorus (monkfish)			
Spanish Atlantic Southwest coast	PCBs	2.512-3.112	(44)
	PCDD/Fs	0.00033-0.00086	
North Sea	dl-PCBs	0.09	(41)
Croatia	PCBs	1.8–3.3	(7)
Merluccius merluccius (hake)			
Bay of Biscay	PCDD/F	0.000086	(5)
Southern Italy	HCB	<dl-0.48	(45)
	DDTs	0.98-9.2	
	PCBs	6.72-101.3	
Adriatic Sea	PCBs	3.41	(42)
	PCDD/Fs	0.00008	
Croatia	PCBs	2.7–4.6	(7)
Atlantic Ocean	dl-PCBs	1.33	(41)
Molva molva (ling)			
Ireland-liver	HCB	31.19	(39)
	PCBs	610.8	
	DDTs	505.24	
	chlordane	160.11	
Mora moro (common mora)			
Mediterranean Sea-liver	DDTs	745–1630	(46)
	PCBs	736–5490	
Mustelus asterias (starry smooth-hound)			
North Sea	dl-PCBs	7.60	(41)
Pagellus acarne (axillary seabream)			
Adriatic Sea	PCBs	1.52	(40)
Phycis blennoides			

Specie, origin and tissue (muscle when not specified)	Pollutant	Concentration (mg/kg ww for metals and µg/kg ww for POPs)	Reference
(greater forkbeard)			
Mediterranean Sea-liver	DDTs	214	(47)
	PCBs	350	
Adriatic Sea	PCBs	0.0011	(42)
	PCDD/Fs	0.0000096	
Pleuronectes platessa			
(European plaice)			
North Sea	dl-PCBs	0.34	(41)
Pollachius virens			
(saithe)			
North Sea	PCDD/F	0.098	(5)
Norway	PCDD/F	0.025	(5)
Mediterraneum Sea	dl-PCBs	0.47	(41)
Raja clavata			
(thornback ray)			
North Sea	dl-PCBs	0.15	(41)
Sardina pilchardus			
(sardine)			
Bay of Biscay	PCDD/F	0.603	(5)
Spanish market	PCDD/Fs	0.00145-0.00239	(48)
	PCBs	0.049-0.0652	
Spanish Atlantic Southwest coast	PCBs	20.9-23.8	(44)
	PCDD/Fs	0.00084-0.00119	
Adriatic Sea	dl-PCBs	0.88	(41)
Scomber scombrus			
(Atlantic mackerel)			
Bay of Biscay	PCDD/F	0.317	(5)
North Sea	PCDD/F	0.330	(5)
North Ionan Sea-liver	HCB	ND-6.07	(49)
	DDE	0.25-104	
	PCBs	0.1-158	
Southern Italy	HCB	<dl-2.83	(45)
	DDTs	<dl-23.8	
	PCBs	2.54-237.8	
Northwest Atlantic	PBDE	7.11	(43)
	HBCD	1.44	
Slovenia	PCBs	8.4-17.4	(7)
Trachurus mediterraneus			
(Mediterranean horse mackerel)			
Adriatic Sea	PCBs	5.2	(42)
	PCDD/Fs	0.000062	
Trachurus trachurus			
(Atlantic horse mackerel)			

Specie, origin and tissue (muscle when not specified)	Pollutant	Concentration (mg/kg ww for metals and µg/kg ww for POPs)	Reference
Adriatic Sea	PCBs PCDD/Fs	6.15 ND	(42)
Trigla lyra (piper gurnard)			
Adriatic Sea	PCBs	0.70	(40)

Table 3. Pollutant content in Fish By-Products

Type and Origin	Pollutant	Concentration (ng/g)	Reference
Fish oil -Mixed (no salmon)	PCDD/Fs	0.00055	(13)
	PBDEs	0.887	
Fish oil-Mixed (including salmon)	PCDD/Fs	0.00157	(13)
	PBDEs	0.898	
Fish oil-Salmon	PCDD/Fs	0.0072	(13)
	PBDEs	3.260	
Fish oil-Shark	PCDD/Fs	0.139	(13)
	PBDEs	57.7	
Fish oil-Menhaden	PCDD/Fs	0.0818	(13)
	PBDEs	50.9	
Fish oil- Fish processing industry blend-Baltic Sea	HCB	12	(51)
	DDTs	337	
	PCBs	197	
Fish oil-unknown	HCH	11.9	(52)
	DDTs	30.0	
	PCB	74.0	
	PBDEs	12.7	
Fish feed-Scottish source	HCH	30.4	(52)
	DDTs	47.9	
	PCBs	157.3	
	PBDEs	16.2	
Fish meal-Peru	PCDDs	0.132	(22)
	PCDFs	0.058	
	DL-PCBs	0.17	
	non DL-PCBs	2.0	
	PBDEs	0.068	
	HCB	0.18	
	DDTs	1.9	
	As	3 (mg/kg)	
	Hg	0.045 (mg/kg)	
	Cd	1.2 (mg/kg)	
	Pb	0.087 (mg/kg)	
Fish oil-Norway	PCDDs	2.48	(22)
	PCDFs	5.2	
	DL-PCBs	21	
	non DL-PCBs	133	
	PBDEs	26	
	HCB	40	
	DDTs	254	
Krill meal-Norway	PCDDs	0.048	(22)
	PCDFs	0.060	
	DL-PCBs	0.072	

Type and Origin	Pollutant	Concentration (ng/g)	Reference
	non DL-PCBs	1.3	
	PBDEs	0.047	
	HCB	1.1	
	DDTs	-	
Fish oil for feed- different sources	HBCD	3.34-26.8	(53)
Fish oil for food-different sources	HBCD	0.19-4.19	(53)