



Environmental assessment of common octopus (*Octopus vulgaris*) from a small-scale fishery in Algarve (Portugal)

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Received: 9 February 2022 / Accepted: 2 June 2022 / Published online: 8 June 2022
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Abstract

Purpose Common octopus is the fishing species with highest economic revenue in Portugal, and its consumption per capita is very high. The majority of catches come from the small-scale fleet with pots and traps. The aims were to assess main environmental impacts of common octopus' fishery with traps and pots in the Algarve region, where the most important fleet size and landings volume occurs, and to find if there are significant differences between both fishing gears.

Methods The assessment includes standard LCA impact categories, fishery-specific impact categories, and quantification of macroplastics and microplastics emitted to the environment. The functional unit selected was 1 kg of octopus and the study was a 'cradle to gate' system. The scope included fishing operations until the product is landed at the harbour. Primary data was obtained by face-to-face questionnaires from 22 vessels, with an average of 1005 pots and 1211 traps per vessel, and 372 pots and 234 traps lost annually to the environment. Plastic pots have a concrete block and traps are a metal framed covered by plastic netting. Each trap or pot is connected to the main line at regular intervals. Unlike traps, pots do not need bait.

Results and discussion Fuel contribution to global warming is very high and where the highest potential exists to lower down the carbon footprint. The fuel use intensity resulted in 0.9 L/kg of octopus. The bait used in traps is significant and raises further environmental costs related with fuel consumption. The use of traps represents more than two times the impacts found for pots in all the categories studied except ecotoxicity categories. Zinc use was the main contributor to ecotoxicity categories, but it has not been included in other fishery LCA studies. It was estimated that 12.2 g of plastics is lost to the environment per kg of octopus. The loss of macroplastics from fishing gears was the highest contributor.

Conclusions The carbon footprint obtained was 3.1 kg CO₂ eq per kg of octopus, being lower compared to other seafood products, and less than half compared to octopus caught with trawling. Pots and traps are highly selective fishing gears, causing negligible disturbance to the seafloor. The stock is not assessed, but management measures exist and can be improved. A drawback exists related with gears lost to the environment.

Keywords Common octopus (*Octopus vulgaris*) · Small-scale fishery · Pots · Traps · Plastic · Cephalopods · LCA · Fuel

Communicated by Ian Vázquez-Rowe

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1 Introduction

Octopuses (*Octopodidae*) are muscular animals with one or two columns of suckers along four pairs of arms, spawn only once at the end of their life cycle, and live between 1 to 2 years (Sauer et al. 2021). Their global distribution is related to their enhanced growth rates, short life spans, opportunistic feeding, and great population turnover, which allow to adapt to environmental changes quicker than fish competitors or predators (Doubleday et al. 2016). More than twenty octopus species are harvested globally, but common octopus (*Octopus vulgaris*) is the main species produced (Josupeit 2008; Sauer et al. 2021). Typically, octopuses are caught worldwide by both industrial fleets (trawlers and jiggers) and small-scale artisanal fleets (Pita et al. 2021). The catch by large-scale fisheries is practically unregulated since octopus are often not the target species (Ospina-Alvarez et al. 2022). Regarding artisanal fisheries, restrictions exist, especially in southern Europe, but due to low enforcement, high levels of illegal, unreported and unregulated (IUU) fishing are assumed (Pita et al. 2021).

Global catches of octopuses increased, almost doubling from 179,042 tonnes in 1980 to 355,239 tonnes in 2014, but biological data for most species are still scarce and in most cases no management of stocks or assessment exists (Sauer et al. 2021). Octopus landings are led by China, Japan, and Spain, and recent decreases in catches in Morocco and Mauritania, two of the most important supplier countries, resulted in more restrictive management measures (Ospina-Alvarez et al. 2022). To support the increasing octopus demand, octopus aquaculture is advancing in different regions due to their appealing features (e.g. rapid growth, short life span, high food conversion rates), and its commercialization is likely to happen in the near future, raising further ethical and environmental concerns (Vaz-Pires et al. 2004; Jacquet et al. 2019).

The European market is one of the most important in the world for cephalopods, especially in southern Europe due to diet traditions and small scale fisheries activity (ICES 2018). Portugal is the second EU member state with the highest octopus' landings, behind Spain (Lourenço 2014). Molluscs started to have a significant production in Portugal in the 1980s and octopus value grew becoming the most important Portuguese seafood product in value (Almeida et al. 2015). Portugal is now an important market for octopus, with exports mainly to Spain and USA, and imports of processed octopus from Spain (Pita et al. 2021).

In 2020, 5227 tonnes of octopus were caught by Portuguese fishing fleet, from which 96.5% came from the artisanal polyvalent fleet, with trawling representing only 3.3% and purse-seining 0.3% (INE 2021). Octopus is the

species with the highest economic revenue in Portugal, with an average price of 6.05 €/kg (INE 2021). However, these figures could be even higher since, as Sonderblohm (2015) suggested, 20% of octopus landings are unreported and black market of landings for underweight octopus is assumed in ICES (2013) report. More than half of octopus landings occur in the Algarve region (DGRM 2021). Over the last 30 years the landings of common octopus in Portugal have more than doubled, however in the last few years landings in Algarve have been decreasing (Pita et al. 2021). The region is the most important for octopus' fishery in terms of fleet size, landings volume, and employment. Algarve has the major fleet dedicated to octopus fishery and landings represented, in 2013, 43% of octopus production in Portugal (CCMAR 2015). The common octopus is the main species caught, and captures with pots and traps account for around 90% of octopus landings volume in Algarve (Moreno et al. 2014). In 2019, 358 vessels were licensed in Algarve region for traps or pots (326 trap and 189 pot licenses as vessels can carry more than one gear license), employing a total of 1501 fishermen (Pita et al. 2021).

The common octopus can grow to a maximum of 10 kg, although its average weight is 3 kg, and lives in habitats with rocks and grass beds along the coastline, usually migrating to deeper waters during winter (EUMOFA 2021). The stock is assessed by the International Council for the Exploration of the Sea (ICES) and the working group on cephalopod fisheries (also named WGCEPH) considers two areas of assessment within Portuguese waters: IXa-North (Portugal) and XIa-South (Gulf of Cadiz, which includes the South of Portugal and Spain) (ICES 2020). However, cephalopods fisheries are excluded from total allowable catch (TAC) or quota regulations from the Common Fisheries Policy (CFP), there is no formal assessment, and the stock abundance is unknown (ICES 2020). Nonetheless, in Portugal, the fishery is subject to specific legislation and management measures that consist essentially of regulations defining a minimum landing weight (750 g) and the number and type of gear used (maximum of 3000 non-baited pots per vessel of any size; trap limits vary according to the vessel length: 750 traps per vessel under 9 m in length, 1000 traps for vessels between 9 and 12 m, and 1250 traps for vessels over 12 m; with restrictions on the mesh size and traps' dimensions) together with spatial–temporal constraints (Sonderblohm 2015).

Small scale octopus' fishery in Algarve uses two types of gears: *covos* or traps and *alcatruzes* or pots. Pots were the main gear used until the 1980s, when traps became more popular (Sonderblohm 2015). Ceramic pots have been replaced in the last years by plastic pots, having similar dimensions. Traps are a small metal framed covered with hard plastic netting and a single entrance on the top (Erzini et al. 2008; Sonderblohm

2015). Traps are baited, usually with a combination of different species that are abundant and have low commercial value compared to other fish species (e.g. Atlantic chub mackerel, sardine, or horse mackerel). The use of live bait (green crab) is prohibited since 2012 only in the Algarve, after the claim by some fishermen that it may allow for the handling of more traps during longer time periods, thereby increasing fishing effort, while also allows the expansion to fishing grounds at greater depths (Sonderblohm et al. 2017; Leitão et al. 2021). Other extra measures in place only in this region include the absence of fishing by the small-scale octopus' fishery during the weekend (only for the south coast of Algarve) (Pita et al. 2021).

Both traps and pots are deployed in ropes with several hundred units and the number of gears has increased remarkably in the last few years (Sonderblohm 2015). Since they are often deployed without signalling buoys to avoid theft coupled with long soak times, the loss of traps and pots is very common (Erzini et al. 2008; Loulad et al. 2017). It usually happens the loss of the entire gear due to bad weather or when fishermen cut the lines to disentangle the gears if they catch a line of traps in their own gear. It has been estimated that 52,604 traps were lost in Algarve waters in 2000 corresponding to a rate loss of 24% of the traps (Erzini et al. 2008). When gears are lost during fishing activities, there is a substantial contribution to plastic pollution (Sauer et al. 2021). For instance, 50% of the marine debris collected in the southern Atlantic coast of Morocco is made of plastic, being 94% from lost pots to capture octopus (Loulad et al. 2017).

The methodology used to assess the fishery was the life cycle assessment (LCA). It provides a standardized and reliable method for the environmental analysis of seafood extraction and derived products throughout the supply chain (Avadí and Fréon 2013). A wide range of LCA studies on fisheries and related products have been performed in recent years, employing common impact categories in LCA, such as those related to air emissions (global warming, ozone depletion, or photochemical ozone formation), toxicity (to seawater, freshwater, or human health), and resource consumption (abiotic depletion or water use), mainly for fish products caught in North Atlantic waters (Ruiz-Salmón et al. 2021). Yet, only one study assessed a cephalopod fishing fleet with trawling in Mauritania waters including onboard processing operations to produce frozen octopus products (Vázquez-Rowe et al. 2012). Due to the importance of this resource and the diversity of production methods, including different fishing gears and degrees of industrialization, and the fact that in Portugal the majority of catches come from pots and traps, it is of foremost interest to assess this small-scale fishery. Since LCA methodology is limited to conventional LCA impact categories, other direct biological impacts inherent to this fishing activity, namely unintended

mortality (e.g. discards and by-catch) or seafloor disturbance, can complete LCA results (Avadí and Fréon 2013; Ruiz-Salmón et al. 2021). Also, current life cycle inventory (LCI) database do not consider plastic losses to the environment. Since a significant proportion of marine plastic debris originates from fishing activities, it is worthwhile to quantify these losses and to identify the main sources of macroplastics and microplastics (Loubet et al. 2022).

Therefore, the overall aim of this study is to assess main environmental impacts of common octopus' fishery with traps and pots in the Algarve region (Portugal), by including (1) standard LCA impact categories, (2) fishery-specific impact categories, and (3) quantification of plastic emitted to the environment, determining also trade-offs between impact categories. The results will enable to understand if there are significant differences between both traps and pots, since the way vessels operate with each gear involve different procedures. It is expected that results will contribute to advance the knowledge on the overall performance of a small-scale fishery, compare it with other fisheries, and make stakeholders more aware about the various aspects when to prioritize environmental improvements.

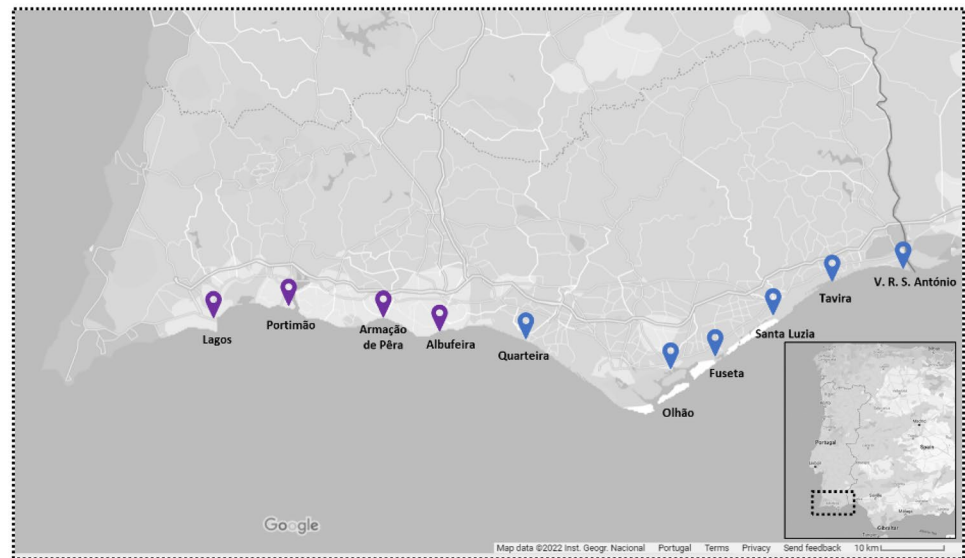
2 Methods

2.1 Scope definition and functional unit

The LCA was performed to estimate the potential environmental impacts of common octopus (*Octopus vulgaris*) fishery with traps and pots. Vessels operate in the continental shelf of Algarve within the inshore limit of 6 NM from the coast, beyond which the trawlers are licensed to operate, covering a ground area of around 2569 km², mostly between 20 to 80 m depth usually in soft bottom (Sonderblohm 2015). The fishing vessels belong to the local fleet, with length overall not exceeding 9 m, and the coastal fleet, with vessels ranging from 9 to 15 m (Pita et al. 2021). Vessels are enforced by legislation to spatial-temporal constraints of a minimum distance from shore at which the gear can be deployed: 0.5 NM for vessels below 9 m in length and 1 NM for vessels over 9 m in length using pots and/or traps, although this varies according to season, as during summer boats can get closer (Pita et al. 2015; Sonderblohm 2015). The fishing area in Algarve is distributed among ten ports and represented by 15 fishing associations (Sonderblohm et al. 2017), vessels can cross the coast from Burgau to Vila Real de Santo António (Fig. 1).

The functional unit (FU) selected is 1 kg of landed octopus, representing the most common presentation of the product in the market and reflecting the function of delivering raw material for further fresh consumption and/or processing by processing industries. The study is a 'cradle

Fig. 1 Fish auctions and sales points for the pots and traps fishery in Algarve divided into the two sub-regions: leeward in purple and windward in blue (maps data: Google © 2022 Inst. Geogr. Nacional)



to gate' system, with all the stages for the extraction, and the scope includes inputs and outputs from fishing operations until the product is landed at the harbour (Fig. 2). Apart from fishing gears and bait, the system boundaries

include other inputs (e.g. diesel, ice, and materials required for vessels' maintenance) needed to land 1 kg of octopus in Algarve. The construction and end-of-life (EoL) of vessels were not included given the high vessels lifetime range (5

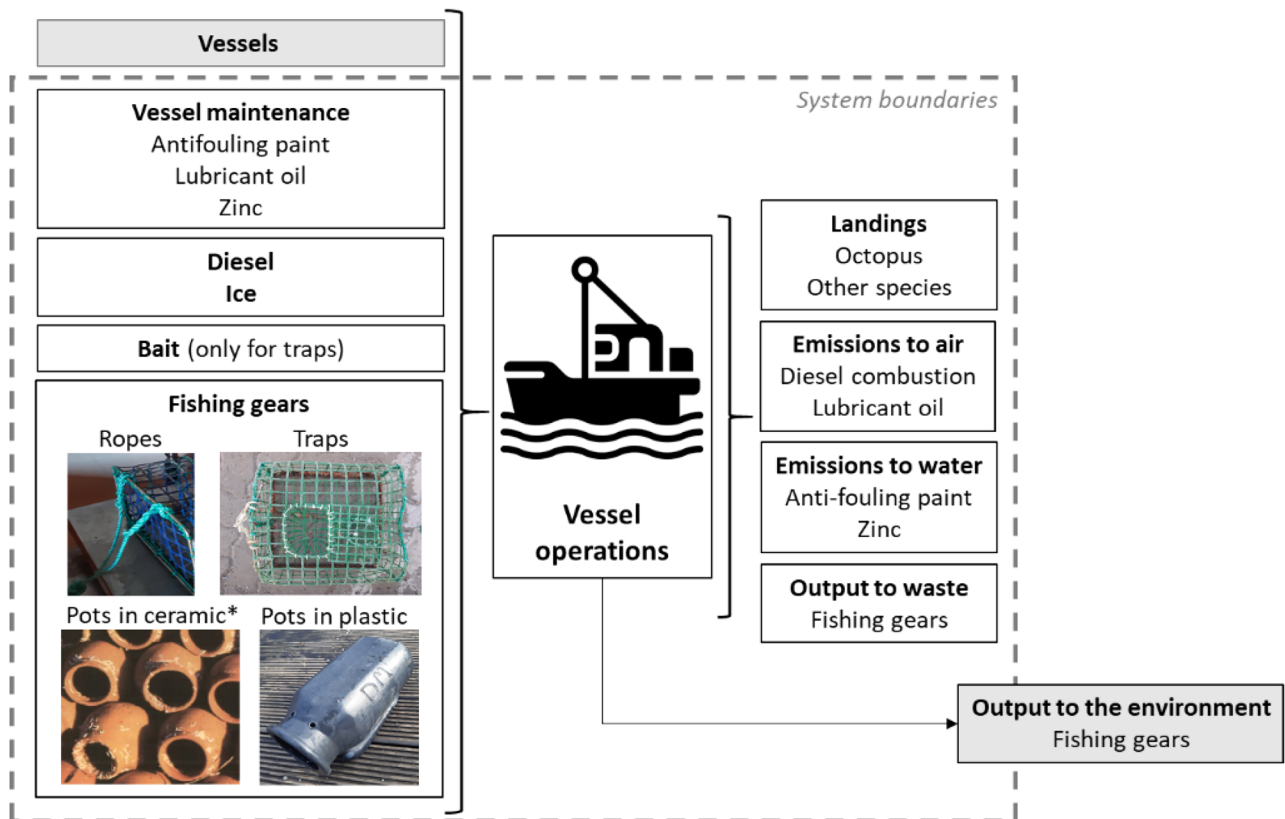


Fig. 2 Flow chart of common octopus fishing operations. The boxes represent inputs, emissions, waste generated, losses to the environment, and products and co-products. The dash box represent the system

boundaries and grey boxes process not included in the system (* from Carneiro et al. 2006)

to 63 years) and difficulty to get light ship weight of vessels. Moreover, due to large volumes of landings, a low contribution to the life cycle inventory was expected. Previous findings showed that capital goods as vessels have minor contribution to the overall environmental impacts of seafood products (Hospido and Tyedmers 2005; Ziegler et al. 2013), representing less than 1% of one or more impacts (Iribarren et al. 2010; Svanes et al. 2011). Since other species are caught together with octopus, it was applied mass allocation in co-product allocation to landings. Economic allocation was avoided due to the volatility in market prices, which can depend on the season or freshness of the product, making it difficult to establish a constant allocation over time (Ruiz-Salmón et al. 2021).

2.2 Description of fishing operations

Vessels make daily trips to their fishing site, where gears are deployed to pull pots and traps onboard and get the octopus. The octopus are by chance inside the pots, since they are not blocked and can escape at any time, or trapped inside baited traps. Fishing gears can stay deployed at the sea for many days and are brought to land whenever it is needed to clean crusted organisms or repair them.

On average vessels had three crew members and worked 159 days per year. Vessels can be made of wood, steel, or fibreglass and are painted annually, during the period that the vessel is transferred to a dockyard for maintenance operations (usually 1 month). Vessels are coated to prevent corrosion, but it is not sufficient to fully protect the ship from corrosion since uncoated sections (e.g. screw, damage) may also exist (Netherlands National Water Board 2008). Therefore, zinc anodes are placed for cathodic protection of metal surfaces, being replaced annually. To improve the capacity and increase the fishing effort, vessels have a mechanical winch (known as *alador*) (Sonderblohm 2015).

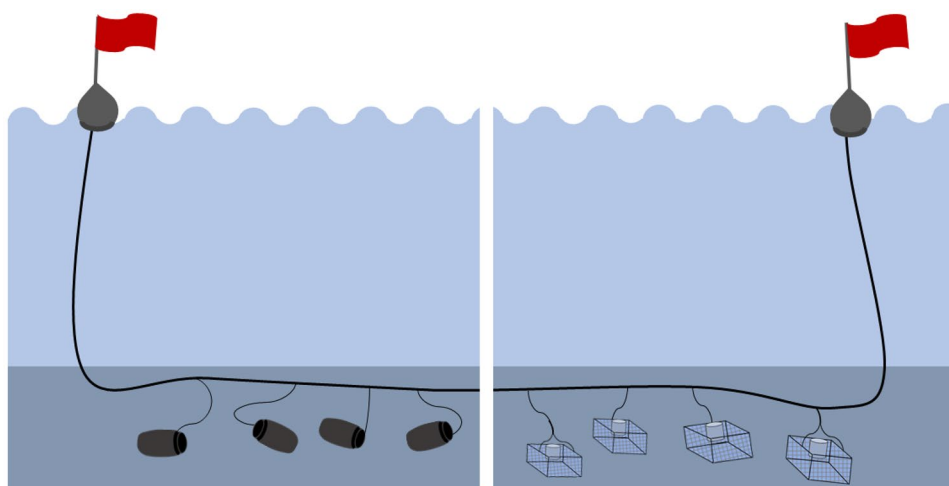
Both ceramic and plastic pots operate likewise, with a small hole at the opposite end to allow the water to go out when the trap is pulled aboard and plastic pots have a concrete block to cancel buoyancy (Sonderblohm 2015). Traps are a small metal framed trap with hard plastic netting of around 3 cm mesh size and have a single entrance on the top which is partially blocked by plastic strips that are easy to push through when entering but not when exiting (Erzini et al. 2008). These traps are of different dimensions and shapes depending on the boat and each trap's owner is easily recognized by local fishermen. Both traps and pots are deployed in ropes known as *teia* (usually 8 mm diameter) with several hundred units. Each trap or pot is connected to the main line by a line of smaller diameter (usually 7 mm diameter) known as *alfoque* at regular intervals of around 8 to 18 m (depending on the vessel procedures). Each *teia* has a rope called the *arinque* at both ends that connects to an anchor weight and to the pulling line ending in a buoy (Fig. 3).

Unlike traps, pots do not need bait. Since the fish bait is consumed by other organisms or deteriorates within 24 h, traps require daily maintenance to replace it. Some vessels prepare the bait in advance by salting the fish during some hours. Traps are baited at the vessel, during the fishing trip. Some fishermen also use part of food packages that have the inside made by aluminium (e.g. 1 kg coffee beans package) or an aluminium foil because it is believed that the metallic surface could visually attract octopus (INE 2019).

2.3 Data collection and assumptions

Primary data was obtained by face-to-face questionnaires answered by skippers at the fishing harbours and sales points of Santa Luzia, Fuseta, Olhão, Albufeira, and Alvor in Portimão (Fig. 1). These questionnaires included a detailed identification of operational aspects of the fishery, such as vessel

Fig. 3 Diagram of the pots (left side) and traps (right side) deployed underwater



characteristics; number of gears, their weight, and materials; paint and zinc quantity used for vessels' maintenance; fuel and other daily consumptions as ice and bait; landings, together with by-catch or discards. The template of the questionnaire is available in the Supplementary Information (SI). The time frame of data collection was one complete year of operations, considering seasonal differences of landings and 2018 was asked as a reference.

The sample used for this study included a group of 22 vessels belonging to small-scale fisheries, corresponding to 12% of octopus catch by the Algarve fleet (2,738,400 kg octopus were landed in the Algarve except trawling and 323,354 kg octopus were the total landings in this study) (DGRM 2021). Vessels differ on the type of gear used. The same vessel can operate with both traps and pots: 9 vessels use traps, 4 vessels use pots made in plastic, 2 vessels use pots both in plastic and ceramic, and 7 vessels use both traps and pots in plastic. The bait used was small pelagic fish species caught by purse seine fishing vessels (e.g. sardine, Atlantic chub mackerel, or horse mackerel). The background data for bait and ice production was obtained from a LCA study about purse seine fishery in Portugal from Almeida et al. (2014). Background data for diesel, lubricant oil, gears' materials (HDPE, concrete, iron, ceramic), paint, and EoL of gears' materials were obtained from Ecoinvent 3.7.1 database (Moreno et al. 2018) (see Table 2 in SI).

To calculate the gear materials per vessel, the total number of gears (pots and traps) was multiplied by the individual weight based on the proportion of materials assumed for each type of gear. Plastic pots weight was calculated assuming that 25% of the total weight corresponds to plastic (HDPE) and 75% to concrete. For ceramic pots, the total weight is ceramic. In case of traps weight, it was assumed that 25% of the total weight corresponds to plastic netting (HDPE) and 75% to iron. The total weight was then divided by the number of years of the lifetime assumed for each gear to obtain a quantity of gear' materials per year. The lifetime of gears was based on information given by fishermen. It was assumed that ropes have a lifetime of 1 year, pots 10 years, and traps 3.5 years. To the weight of gears obtained per year, it was added the weight of fishing gears that are lost in the environment annually per vessel. These values were based on answers to the questionnaires. Ropes were assumed to be made of HDPE and their output was assumed only to go to waste (not lost in the environment).

The waste of materials used in the fishing gears was included in the overall modelling of LCA following PEF methodology, which recommends modelling EoL using the Circular Footprint Formula (CFF).¹ The CFF is a combination of material with energy and disposal, and default

values of these parameters are available in Tables 1 and 2 in SI. It was assumed that the amount of gears' materials that are replaced annually go to waste. This is not the case for ceramic pots, which were assumed to stay in the environment once they are unfeasible to be used.

The emissions related to the consumption of fuel by fishing vessels were added with emission factors from pollutants emitted by fuel combustion for small recreational boats (EMEP/EEA 2019) and IPCC report (Eggleston et al. 2006). Emissions related to the consumption of lubricant oil to be applied in the winch equipment and engine were added with emission factors for hydraulic fluid and engine oil from EMEP/EEA (2019). Direct emissions to the water derived from the use of antifouling paint to the marine environment were quantified as a typical loss of two-thirds of the coating that is degraded at the sea (Hospido and Tyedmers 2005). The rest, one-third of the coating was considered to be treated ashore.

Apart from data collected through face-to-face questionnaires, octopus' landings and fuel use data for the overall Portuguese fleet for 2015 (1299 vessels) and 2018 (1231 vessels) was provided by the Portuguese Directorate-General for Natural Resources, Safety and Maritime Services (DGRM). These data were used to compare fuel use per kg of octopus caught using overall lengths of vessels to establish two categories: "artisanal" or "small-scale" fisheries defined as fishing done by vessels under 12 m, not using towed gear and targeting multiple species using traditional gears (1123 vessels in 2015 and 1058 in 2018); and "industrial" fisheries done by vessels with 12 to 24 m (176 vessels in 2015 and 173 in 2018) (Villasante et al. 2018). Landings were also divided between harbours in Algarve and in the rest of Portugal.

2.4 Life cycle inventory

From the 22 vessels assessed, it was obtained an average of 1005 pots and 1211 traps per vessel, and 372 pots and 234 traps lost annually to the environment. The inventory data has detailed quantities of the different materials used and resources consumed to catch octopus with pots and traps, as well as products and emissions, including materials that go to waste management or to the environment.

An average for overall vessels sampled is shown in Table 1 together with a subsample for vessels using only pots or traps. From the life cycle inventory data, it is possible to recognize the selectivity capacity of fishing gears since on average only 0.04 kg of other species are caught per 1 kg of octopus. In the case of pots, the selectivity is total, with a catch made 100% of octopus. In terms of bait used by traps, it is necessary on average 0.7 kg of bait to catch 1 kg of octopus which can reach 1.1 kg when only vessels using

¹ https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf

Table 1 Inventory data for octopus fishing with pots (P) and traps (T) (average values and standard deviation (SD) per FU = 1 kg of octopus for overall vessels and vessels only with pots or with traps)

Inputs		Unit	Overall (n = 22)	SD	Pots (n = 6)	SD	Traps (n = 9)	SD
Fishing gears	P — HDPE	kg	0.009	0.024	0.019	0.008	-	-
	P — Concrete	kg	0.027	0.072	0.056	0.025	-	-
	P — Ceramic	kg	0.001	0.006	0.011	0.010	-	-
	P — Polyethylene (ropes)	kg	0.021	0.038	0.048	0.020	-	-
	T — Iron	kg	0.047	0.084	-	-	0.081	0.173
	T — HDPE (plastic net)	kg	0.016	0.028	-	-	0.027	0.058
	T — Polyethylene (ropes)	kg	0.033	0.044	-	-	0.049	0.069
	Other materials and fuel							
	T — Bait	kg	0.706	1.020	-	-	1.082	1.766
	T — Salt	kg	0.009	0.047	-	-	0.000	0.000
	T — Coffee bags	kg	0.000	-	-	-	0.000	0.000
	T — Ice	kg	0.014	0.066	-	-	0.022	0.130
	Diesel	litres	0.818	1.124	0.406	0.311	0.907	0.878
	Paint (antifouling type)	litres	0.001	0.003	0.001	0.001	0.002	0.006
	Engine oil	litres	0.008	0.016	0.008	0.009	0.009	0.017
	Hydraulic fluid	litres	0.001	0.002	0.001	0.001	0.000	0.001
	Zinc	kg	0.001	0.001	0.002	0.003	0.001	0.001
Outputs								
Products	Octopus	kg	1.000	-	1.000	-	1.000	-
	Other species	kg	0.043	0.166	0.000	-	0.032	0.131
Outputs to the technosphere — fishing gears to waste treatment	P — HDPE	kg	0.002	0.004	0.004	-	-	-
	P — Concrete	kg	0.006	0.013	0.013	-	-	-
	P — Polyethylene	kg	0.022	0.041	0.054	-	-	-
	T — Iron	kg	0.031	0.066	-	-	0.056	0.144
	T — HDPE (plastic net)	kg	0.010	0.022	-	-	0.019	0.048
	T — Polyethylene	kg	0.033	0.044	-	-	0.049	0.069
Emissions to the environment — fishing gears lost	P — HDPE	kg	0.007	0.021	0.014	0.006	-	-
	P — Concrete	kg	0.021	0.063	0.042	0.019	-	-
	P — Ceramic	kg	0.000	0.000	0.004	-	-	-
	T — HDPE (plastic net)	kg	0.005	0.009	-	-	0.008	0.015
	T — Iron	kg	0.016	0.026	-	-	0.025	0.046
	Zinc	kg	0.001	0.001	0.002	0.003	0.001	0.001
Emissions to the ocean	Paint (antifouling type)	litres	0.000	0.001	0.000	0.000	0.001	0.002
Emissions to the atmosphere	Carbon dioxide	kg	2.182	2.999	1.083	0.806	2.421	2.343
	Methane	g	0.125	0.172	0.062	0.046	0.139	0.134
	Nitrogen oxides	kg	0.027	0.037	0.013	0.010	0.030	0.029
	Carbon monoxide	kg	0.014	0.019	0.007	0.005	0.015	0.015
	NMVOC	kg	0.005	0.007	0.003	0.002	0.006	0.006
	TSP	kg	0.003	0.004	0.002	0.001	0.004	0.003
	Particulates < 10 um	kg	0.003	0.004	0.002	0.001	0.004	0.003
	Ammonia	g	0.005	0.007	0.002	0.002	0.005	0.005
	Sulphur oxides	kg	0.007	0.010	0.003	0.003	0.008	0.007

traps are analysed. Another relevant input is diesel which is on average half of the value in the case of vessels only using pots comparing to the overall average of vessels. Emissions to the atmosphere are related to diesel combustion and follow the same pattern.

2.5 Impact assessment: methodology

The average of all inputs and outputs identified was calculated for the overall vessels sampled and only for vessels using pots or traps. These values were used to estimate

different environmental indicators and establish the environmental impact of octopus fishing with traps and pots. The life cycle impact assessment step was carried out using the ReCiPe 2016 v1.1 in Hierarchist perspective methodology at the midpoint level (Huijbregts et al. 2017). Eight conventional impact categories were selected and analysed according to the type of impacts more frequently applied in seafood LCA studies (Ruiz-Salmón et al. 2021): global warming (GW) and stratospheric ozone depletion (SOD) to establish the impacts on the atmosphere and the ozone layer related to gaseous emissions; freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), and marine ecotoxicity (MET) to quantify the impacts on fresh and marine water; and mineral (MRS) and fossil resource scarcity (FRS) to establish a link with minerals used in the gears and fuel consumption as it is a main hotspot in fishing activities. SimaPro v9.2 (PRé Consultants 2021) was the software used to lead the computational implementation of the life cycle inventories. In addition, fuel use intensity (FUI) expressed in terms of the litres of fuel burned per live weight landings (usually in tonnes) was calculated per vessel to compare fuel consumption between vessels. Fuel consumption by fishing vessels is typically the dominant driver of energy demand and GHG emissions from fisheries production and there is a marked variation both across and within fleets in the amount required (Tyedmers et al. 2005; Parker et al. 2018).

The lifecycle of seafood commodities differs from that of terrestrial production systems in their diversity but also, in the case of fisheries, in the reliance on extraction of a natural resource, impacts on unmapped ecosystems (e.g. seafloor) and complex trophic webs of aquatic ecosystems (Avadí et al. 2018). To capture also these impacts, five fisheries-specific impact categories were applied: (1) stock assessment and management, (2) by-catch and discards, (3) seafloor disturbance, (4) mean trophic level (MTL), and (5) primary production required (PPR). The stock assessment can be analysed with lost potential yield (LPY) as a midpoint impact category to quantify overfishing applying the maximum sustainable yield (MSY) concept, by comparing the outcome of current with target fisheries management (Emanuelsson et al. 2014). However, it can be used only on stocks for which the required input data are available, which is not the case for octopus since there is no MSY for this commercial species. Due to lack of specific data for this impact category, only qualitative data was used based on previous reports or published papers. By-catch are unintended mortality that is landed, or returned to the sea in the case of discards, given as a percentage of landings and provided as a value referred to the selected FU (kg per FU) (e.g. Ziegler et al. 2011). The seafloor disturbance (m² per

FU) accesses the impact on the benthic ecosystems usually by calculating the seafloor area swept (e.g. Nilsson and Ziegler 2007). The MTL is based on each species trophic level and their proportion in the total catch (Hornborg et al. 2013). The trophic levels (TL) were obtained from Torres et al. (2013) which defined a TL of 3.92 for common octopus, a 3.16 for small demersal fishes and 2.67 for benthic invertebrates, the two main group species found in the octopus' fishery landings. The biotic resource use is based on the PPR needed to produce 1 kg of the harvested species at a certain trophic level (Pauly and Christensen 1995). This impact category quantifies the human appropriation of primary production as a resource that has ecological impacts when removed (Cashion et al. 2016). It also allows comparing products along the seafood supply chain among wild and farmed products, and diverse food systems, including terrestrial ones (Avadí and Fréon 2013). The PPR was estimated as Eq. (1) (Pauly and Christensen 1995; Hornborg et al. 2013; Cashion et al. 2016):

$$PPR = \sum_i \left(\frac{Y_i}{M} \right) \times \left(\frac{1}{TE} \right)^{(TL_i - 1)} \quad (1)$$

where Y_i is the yield for species i (measured as average landings per vessel for 1 year), M is the ratio of wet weight biomass to carbon content of the species of interest, TE is the trophic transfer efficiency of the source ecosystem expressed as a whole number, and TL is the trophic level of the species i . It was assumed that M followed a conservative 9:1 conversion ratio of wet weight to carbon (Pauly and Christensen 1995). A TE of 14.9% was used for this octopus' fishery based on a mean transfer efficiency between trophic levels specific to an ecosystem similar to the Algarve region about Gulf of Cadiz (North-eastern Atlantic) (Torres et al. 2013).

2.6 Quantification of plastic losses

Octopus fisheries rely on large quantities of plastics (e.g. fishing gears, ropes, marine coatings) and associated processes (e.g. manufacturing, use, EoL) might generate plastic losses in the environment. We propose to map the plastic flows within the technosphere and to the environment for the production of octopus from the vessels studied. We used the methodology from Loubet et al. (2022) in order to compute plastic losses to the environment. Considering the boundaries of this study, we only consider three activities (fishing, plastic production, and plastic waste management) and four types of plastic losses:

- Abandoned, lost, or discarded fishing gears during fishing activities (macroplastics),

Table 2 Summary of plastic loss rates and final release rates to the environmental compartments considered in this study

Type of losses	Source of data	Initial loss rate		Final release rate after transport			
		Average	Max	Ocean	Freshwater	Soil	Terrestrial
Fishing gears (traps and pots) — macroplastics	Primary data from this study	From vessels (LCI data)		100%	0%	0%	0%
Marine coatings — microplastics	Verschoor et al. 2016	1.20%	3%	100%	0%	0%	0%
Plastic pellets — microplastics	Peano et al. 2020	0.01%	0.10%	11.74%	5.09%	65.66%	3.61%
Mismanaged plastics at the EoL, Portugal data — macroplastics	Peano et al. 2020	0%	4.3%	25%	0%	0%	75%

- Marine coatings applied to boats that leak during fishing activities (microplastics),
- Plastic pellets that can be lost to the environment during plastic production in the background (microplastics) and,
- Mismanaged plastics during the EoL (macroplastics).

Loss rates for abandoned, lost, or discarded fishing gears during fishing activities were directly computed from primary data gathered in this study (Table 1). Loss rates for other plastic losses were taken from literature sources identified in Loubet et al. (2022). Two scenarios were set up, with average and max values, as there can be a large variability in these loss rates (Table 2). This is particularly the case for the mismanaged waste at the EoL. The Plastic Leak Project (Peano et al. 2020) considers that 100% of plastics are well managed at the EoL in Portugal (i.e. loss rate of 0% at the EoL), which is based on one single data related with waste collection rates from only one city in Portugal (Kaza et al. 2018). Since this value might be underestimated, we considered for the max scenario plastic loss rate at the EoL equal to 4.3%, which is the default value for high income countries (Kaza et al. 2018). Final release rates after transport between environmental compartments were directly taken from (Loubet et al. 2022). Loss and final release rates were applied and computed for each vessel per FU (1 kg octopus). Different averages are computed considering the overall vessels, and the pots or traps ones.

3 Results

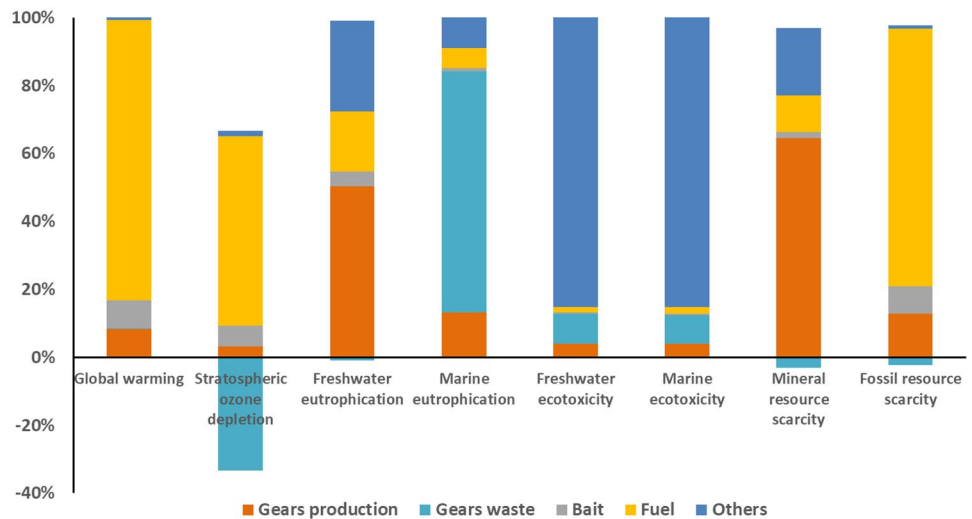
3.1 Life cycle impact assessment results for the selected categories

The environmental impacts in the octopus' fishery for the selected impact categories are shown in Table 3 with breakdown of the results for the main items included in the LCI. The grouping "Others" comprises the rest of the items, including ice, paint, engine oil, hydraulic fluid, and zinc. The catch of 1 kg of octopus with pots and traps results in 3.09 kg CO₂ eq and the climate change impact is heavily related with the energy/fuel used by vessels during fishing operations. The production of materials for the gears and bait is in the second level of importance, representing together around 16%, showing the relative low relevance of other inputs (Fig. 4). The fuel, including its production and combustion, is the principal item contributing to GW, SOD, and FRS, representing 82%, 168%, and 79% respectively. Fuel use contributes to more than 100% of the SOD category because gears waste is partly recycled and avoids the production of primary materials according to the CFF formula, resulting in negative figures for SOD (−100%), MRS (−3%), and FRS (−2%). The gears were the most important item related to eutrophication, for the FE the main contribution comes from gears' materials production (51%) and iron from traps represented half of this contribution. On the

Table 3 Characterization values for octopus' fishery with pots and traps for FU

Impact category	Unit	Total	Gears production	Gears waste	Bait	Fuel	Others
Global warming	kg CO ₂ eq	3.09	0.25	0.01	0.26	2.55	0.02
Stratospheric ozone depletion	mg CFC11 eq	0.40	0.04	−0.40	0.07	0.67	0.02
Freshwater eutrophication	g P eq	0.12	0.06	0.00	0.01	0.02	0.03
Marine eutrophication	mg N eq	40.48	5.31	28.73	0.45	2.38	3.60
Freshwater ecotoxicity	kg 1,4-DCB	0.22	0.01	0.02	0.00	0.00	0.19
Marine ecotoxicity	kg 1,4-DCB	0.31	0.01	0.03	0.00	0.01	0.27
Mineral resource scarcity	g Cu eq	4.63	3.19	−0.15	0.09	0.53	0.98
Fossil resource scarcity	kg oil eq	1.07	0.14	−0.03	0.09	0.85	0.01

Fig. 4 Comparison of the relative contributions for the octopus' fishery with pots and traps for FU



other hand, for ME, the main contribution comes from the materials waste (71%), especially from processes associated to sanitary landfilling. In the case of MRS, it follows the FE pattern, having gears' materials production as the main contributor (69%), mainly due to the iron used in the traps. For both cases FET and MET, the main contribution comes from "Others", contributing in both 85%, which is linked directly with zinc production and consumption by vessels, since it represents 77 and 78% respectively of FET and MET results (0.17 and 0.24 kg 1,4-DCB).

Differences of environmental impacts between fishing gears were analysed (Table 4) and the use of traps represents more than two times the GW, SOD, FE, ME, MRS, and FRS compared to pots. For FET and MET, an opposite trend was registered, resulting in almost half for vessels using traps. These results are related with the zinc use, since this metal was the main contributor to FET and MET categories, and even representing a small amount overall per FU (0.001 kg per 1 kg of octopus), its contribution is two times greater for vessels using pots (0.002 kg per 1 kg of octopus) compared with traps.

Table 4 Characterization values for octopus' fishery for FU for vessels only using pots and traps

Impact category	Unit	Pots	Traps
Global warming	kg CO ₂ eq	1.49	3.55
Stratospheric ozone depletion	mg CFC11 eq	0.03	0.53
Freshwater eutrophication	g P eq	0.07	0.17
Marine eutrophication	mg N eq	21.51	56.14
Freshwater ecotoxicity	kg 1,4-DCB	0.42	0.27
Marine ecotoxicity	kg 1,4-DCB	0.60	0.37
Mineral resource scarcity	g Cu eq	2.11	7.18
Fossil resource scarcity	kg oil eq	0.53	1.22

The fuel consumption analysis for the FU represents 0.88 L of fuel per 1 kg of octopus caught (Fig. 5). When average is quantified only for vessels with traps (1.21 L/kg), the fuel use almost doubles the value compared to vessels with pots (0.50 L/kg) and its difference has statistical significance (Mann–Whitney *U* test, $p=0.012$). Also, a higher variability was found in fuel use for vessels with traps when compared with pots. Such difference between fishing gears might be related to differences associated with procedures, number of days at the sea, or distance travelled by vessels using traps, which can be very different among vessels influencing then the fuel consumption.

It would be expected that FUI obtained for the vessels analysed in this study was in the same range as the overall

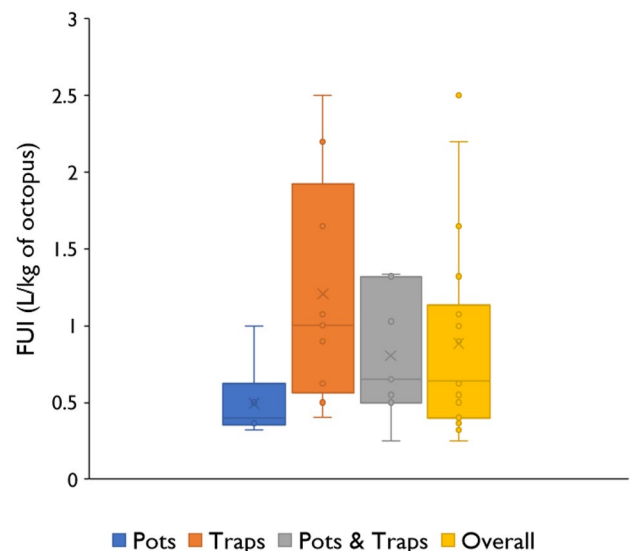
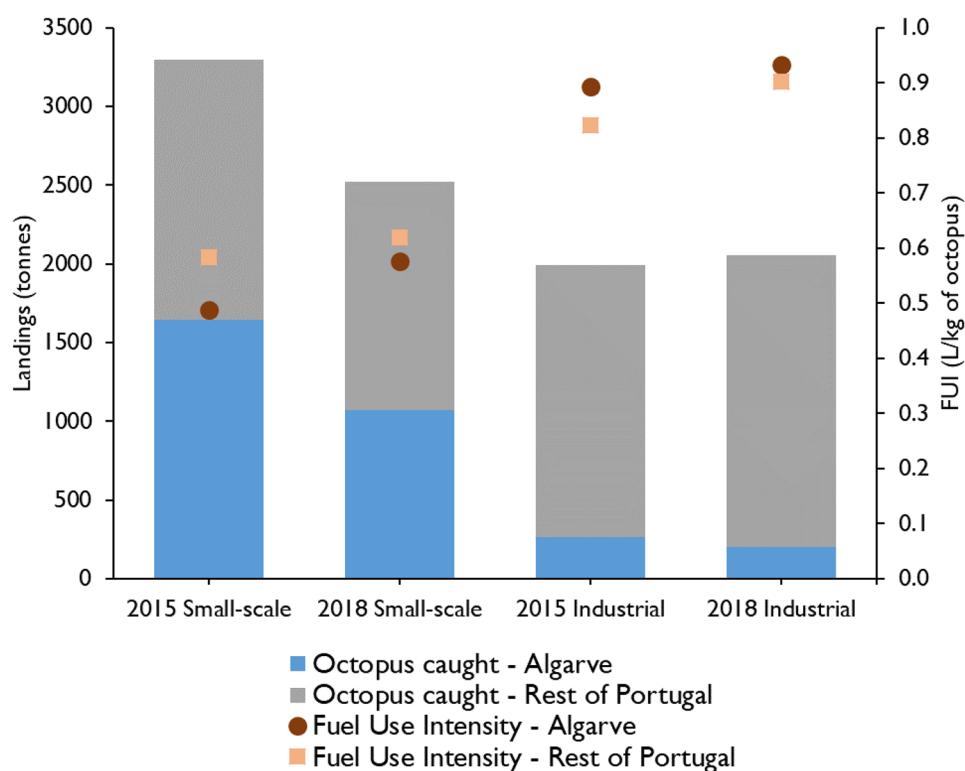


Fig. 5 FUI per landings of octopus for vessels with the different gears assessed

Fig. 6 Landings and FUI per FU (1 kg of octopus) for Portuguese fleet considering small-scale (0–12 m length) and industrial fishing (12–24 m length)



average of FUI obtained for small-scale fisheries; however, values obtained were in the same order as industrial fisheries (Fig. 6). Data for Portuguese octopus' landings were analysed between 2015 and 2018 and it was obtained a FUI on average of 0.53 L of fuel per 1 kg of octopus caught with small-scale fisheries (vessels with 0–12 m) in Algarve (0.49 L/kg in 2015 and 0.58 L/kg in 2018). In the case of industrial fisheries (vessels with 12 to 24 m length), landings in Algarve had a much lower proportion of catches, showing the importance of this small-scale fishery in octopus' landings, and FUI was almost the double compared to small scale fisheries, with 0.91 L of fuel per 1 kg of octopus (0.89 L/kg in 2015 and 0.93 L/kg in 2018). FUI for small scale fisheries in the rest of Portugal was 0.60 L/kg (0.58 L/kg in 2015 and 0.62 L/kg in 2018) and was similar to the FUI obtained to Algarve. In the case of industrial fisheries in the rest of Portugal, the FUI was lower than in Algarve but within the same range, with 0.86 L/kg (0.82 L/kg in 2015 and 0.90 L/kg in 2018).

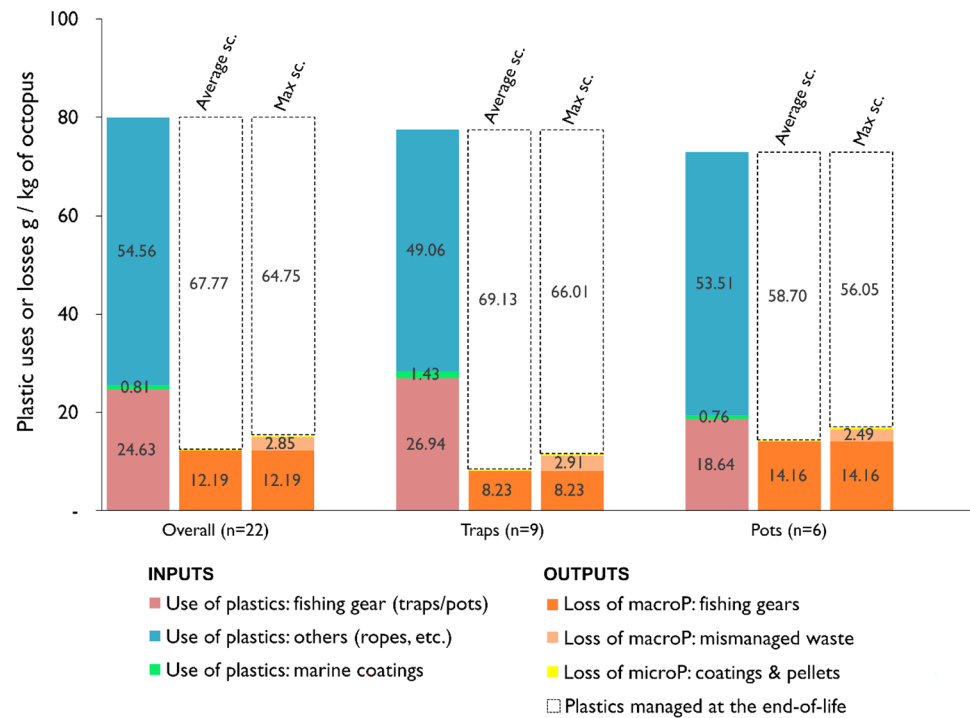
3.2 Fishery-specific environmental impacts

The biological aspects, such as common octopus' stock assessment, by-catch and discards, seafloor impact, MTL, and PPR were evaluated and, as far as possible, quantified (Table 5). The impact category related with stock assessment and management was based only on qualitative data from reports or published papers. Octopus species is excluded

from management through a quota system and there is no MSY for the stock. National programs (e.g. fish auction sampling) provide support for management advice, but current fisheries monitoring system and stock assessment practices in Portugal might be inadequate for this species (Pita et al. 2015). The *O. vulgaris* is a short-lived species and environmental factors (such as upwelling intensity, temperature, and fresh water from land) affect significantly the annual reproduction cycle, controlling timing, intensity, and synchronism, as well as the survival of pelagic paralarvae (Lourenço et al. 2012; Moreno et al. 2014). This might explain in part the significant fluctuations seen in octopus annual landings over time (reaching a variability of 40% per year) (Pita et al. 2015; Sonderblohm et al. 2017). Yet, abundance varies widely from year to year with no clear trends (ICES 2020). A possibility to manage such a species with a fluctuating stock can be a real-time assessment using depletion models, where MSY is not applicable, and harvest rates are based on mean latent productivity (e.g. harvest control rules of a TAC cannot exceed the average latent total productivity estimated from previous years) (Roa-Ureta et al. 2021).

On the contrary to other species/stocks, Portugal is responsible for managing its own octopus' fishery. The management is under the Portuguese fishery management authority, with input from governmental authorities, employing rules to the entire coast with the exception of the prohibition of using live bait in the Algarve (Silva et al. 2019; Pita et al. 2021). The degree of compliance with management measures is minimal,

Fig. 7 Plastic uses and losses for octopus fishing with pots, traps, and overall vessels. Average and max scenarios are represented



and there is evidence that the number of octopus fishing gears in the water far exceeds what is legally permitted (Pita et al. 2015, 2021). Besides, there is no effectively control on the fishing effort (Sonderblohm et al. 2017). As an example, it is difficult to confirm the number of traps per boat and technical characteristics of the traps when deployed, and output control is limited to the minimum weight established (750 g).

The by-catch and discards data were obtained through primary data from this study. The by-catch was registered only to landings from traps representing 4.3% and it was related to many different species, namely seabreams (*Diplodus spp*), Lusitanian toadfish (*Halobatrachus didactylus*), small red scorpionfish (*Scorpaena notata*), pouting (*Trisopterus luscus*), European conger (*Conger conger*), greater forkbeard (*Phycis blennoides*), and purple dye

murex (*Bolinus brandaris*). Discards were related only to octopus under the limited weight (750 g) since landings of those individuals are not allowed. However, it was not possible to collect a quantitative value of discards because it is never weighted during fishing operations. Apart from being entirely selective for octopus, pots have an extra level of selectiveness due to their relatively large size which targets mostly subadult and adult individuals (Sauer et al. 2021).

The seafloor disturbance accesses the impact on benthic ecosystems by calculating the seafloor area swept. Since pots and traps are passive and lightweight fishing gears that stay still in the bottom, they have a negligible impact on the habitat when the fishery is undertaken on rocky, sandy, or muddy bottoms, where the fishery normally occurs. In the case of pots, the octopus voluntarily enters the pot seeking shelter and can leave it at any moment. Therefore, it was considered that no impact occurs to the seafloor.

The MTL of the octopus' fishery with pots and traps is 3.8. It is a MTL close with, for example, the Portuguese purse seine fishery that catches mainly small pelagic fish, with a MTL of 3.1 (Almeida et al. 2014). Besides, it is a MTL under the TL 4, which relates with species as, for example, sharks (TL = 4.07), anglerfishes (TL = 4.84), and hake (TL = 4.11) (Torres et al. 2013). Therefore, the MTL of this fishery relays on a relative less marine food web depletion and lower impact to the marine ecosystem comparing to other fisheries that catch species with higher trophic levels.

Table 5 Fishery-specific environmental impacts values for octopus' fishery with pots and traps for FU

Impact category	Unit	Value/description
Stock assessment and management	-	No stock assessment, TAC or quota
Landed by-catch	kg per FU/%	0.04/4.3%
Discards	kg per FU	0
Seafloor disturbance	m ² per FU	0
Mean trophic level (MTL)	-	3.84
PPR/landings	kg C/kg	26.75

The PPR needed to produce 1 kg of common octopus is 26.75 kg C (432,848.52 kg C is the total PPR). The same indicator applied to purse seine fishery gave a value of 14.61 kg C per kg of landings (Almeida et al. 2014). Therefore, this indicator is higher comparing to a fishery with landings made mainly by small pelagic fish, as for example sardine, which have lower TLs than octopus. Nevertheless, the PPR obtained might be lower than fisheries that catch species, as for example, demersal fish which consequently will present landings with higher TLs and require a higher amount of primary production to deliver 1 kg of catch.

3.3 Plastic generated analysis

Figure 8 shows that 12.2 g of plastics is lost to the environment per kg of octopus, for the average scenario. In this scenario, loss of macroplastics from fishing gears is the highest contributor with 99% (12.19 g), loss of microplastics from plastic pellets (0.016 g), and from marine coatings (0.007 g) are minor contributors. The plastic leakage per kg of octopus is higher than what have been found in the case studies from Loubet et al. (2022), where plastic losses ranged from 0.07 to 4.34 g of plastics per kg of fish, when considering the average scenario

and full life cycle with packaging. This is because octopus fisheries rely on high quantity of plastics per FU, and because traps and pots have a high loss rate. Loss rate for traps and pots fishing gears is 22% on average and is similar to the rate found in the bibliography by Richardson et al. (2019), which is 20%. Also, fishing with trap rely on higher plastic requirement (76.00 g of plastics used/kg of octopus) than fishing with pots (72.15 g of plastics used/kg of octopus). On the contrary, fishing with pots generates more plastic losses from fishing gears (14.16 g loss/kg of octopus) than with traps (8.23 g loss/kg of octopus) (Fig. 7).

The max scenario considers part of the plastics mismanaged at the EoL (4.3%), and higher loss rates for plastic pellets and marine coatings (Table 2). Plastic losses for this scenario are mapped in Fig. 8, showing that 15.14 g is lost to the environment per kg of octopus: 77% (12.19 g) coming from lost fishing gears, 22% (2.85 g) from mismanaged waste, and the remaining from plastic pellets (0.07 g) and marine coatings (0.04 g). In this scenario, 85.58% of plastics end up in the marine environment, 14.46% in the soil and other terrestrial environment (mostly coming from mismanaged waste), and less than 0.1% in freshwater (from microplastics pellets). Detailed results on the destination of the plastic losses into the environment is provided in SI.

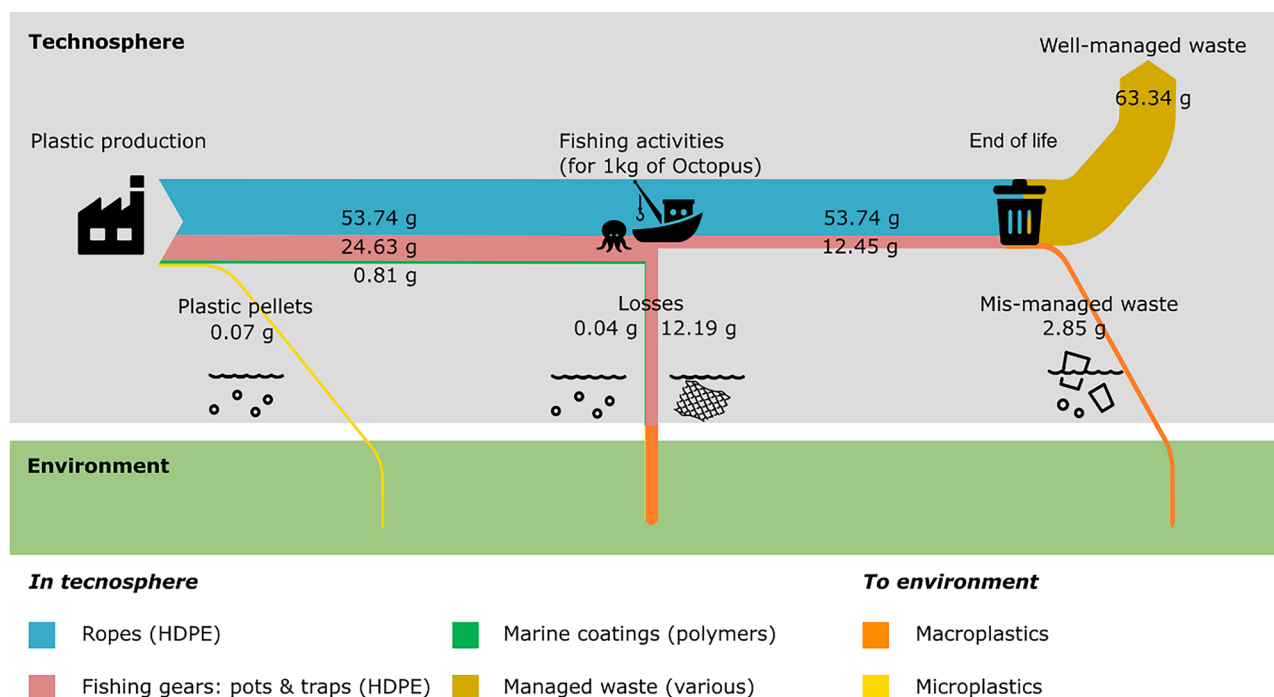


Fig. 8 Major plastic flows in the technosphere and leaching to the environment from the processes associated with octopus fishing (1 kg octopus). The width of flows is proportional to plastic weight.

Max scenario is represented in order to show potential leakages from mismanaged waste

4 Discussion

4.1 Major contributions to environmental impacts of octopus's fishery with traps and pots

This study is a first environmental assessment of an important marine resource in particular to the Algarve region, but also to the Portuguese fishing sector. The carbon footprint obtained in this study, corresponding to 3.1 kg CO₂ eq per kg of octopus, is lower when compared to other seafood products. As an example, Gephart et al. (2021) calculated GHG emissions to edible weight of seafood products and the value obtained in this study for octopus is in the level of fisheries of small pelagic fish, like herring and sardine (3.9 kg CO₂ eq/kg) (Gephart et al. 2021). The carbon footprint is also less than half compared to octopus caught by trawling, the only octopus' LCA study from Vázquez-Rowe et al. (2012), related with the environmental burdens of frozen octopus from the Mauritanian EEZ caught with trawling. The study found that onboard activities which embrace a large number of operations (extraction, processing with weighing, gutting, and freezing) had the highest contribution and there was a dominance of fishing activity, resulting in 7.7 kg CO₂ eq for 1 kg octopus caught (184.6 kg CO₂ eq for the FU of 24 kg) (Vázquez-Rowe et al. 2012).

The highest potential to lower down the carbon footprint is by improving the fuel use as fuel contribution to global warming is very high (84%). This is directly linked to individual procedures followed by each crew, but it is also a consequence of the few inputs needed overall and their small contributions to the carbon footprint. The fuel use is also a main difference between the octopus caught with pots, traps, or trawl. When applying a diesel density of 0.85 kg/L, to convert diesel from litres to kg, we obtained a value of 0.69 kg of diesel per 1 kg of octopus landed. In Vázquez-Rowe et al. (2012) study, it was obtained a value of 1.74 kg of diesel per 1 kg of octopus caught with trawl (41.7 kg for the FU of 24 kg octopus), representing two and a half times more fuel per amount of octopus produced.

The FUI analysis resulted in 0.89 L of fuel per 1 kg of octopus caught, resulting in a FUI of 890 L/tonne. This value is in accordance with those reported by Parker et al. (2018), in a study on fuel use in different fisheries around the world, with an average value of 613 L/tonne reported for all types of cephalopods fisheries. However, the FUI found in this study, of 0.89 L/kg of octopus for Algarve, is similar to FUI of industrial fisheries and higher than expected when compared to the average of Portuguese small-scale fisheries, with 0.57 L/kg. The main reasons that might explain this discrepancy can be either because statistics underestimated consumptions from fishing

vessels or data from questionnaires do not account for all landings since vessels might use other fishing gears apart from pots and traps.

The bait used in traps is significant and has consequently economic and environmental costs that need to be approached. The fish used in the bait has a low cost and high abundance in the region. Also, it is produced with low environmental impacts as known from previous studies about small pelagic fisheries with purse-seine (e.g. Almeida et al. 2014). However, if on average, 0.7 kg of bait is needed to catch 1 kg of octopus, which can reach 1.1 kg for vessels using only traps, these fish would rather represent a more efficient use of resources if it was consumed as food directly. Furthermore, buying bait daily adds an extra cost to traps when compared with pots. To this, extra cost is also needed to add the cost associated to a higher fuel consumption coming from the daily operations to replace the bait in employed traps. Live bait (green crab), prohibited in the Algarve region, was an alternative introduced in the 2000s that allows deployment of traps for longer periods of time (Sonderblohm et al. 2017). Leitão et al. (2021) have found no evidences to support the idea that crab bait result in higher octopus fishing effort or increased landings. Thus, more studies are needed to fully understand trade-offs of this measure as if it allows a reduction in fuel consumption and consequently in economic costs of operations. Another example is the lack of evidence that the use of coffee packaging in the traps results in a higher rate of octopus catches with traps, but then again it adds more rubbish to lost traps with further consequences to the marine ecosystem.

The use of zinc was the main contributor to ecotoxicity impact categories. On the contrary to other LCA studies, where the production and consumption of anti-fouling paints presented a relevant impact for ecotoxicity impact categories (e.g. 98.9% and 40.5% in MET and FET categories respectively, in Cortés et al. (2021)), zinc overlapped as the main contributor in this study. Zinc is a common requirement to avoid degradation of vessel and engine related with rust abrasion, but it seems that it was not included in fishery LCA studies previously. Even though toxicity impacts of metals can be overestimated in LCA, due to their persistence in the environment as metals undergo transitory states and chemical reactions induce a nonlinear impact over time (Lebailly et al. 2014), it cannot explain the absence of this outcome in other LCA studies. It should be highlighted that zinc data had high variability between vessels, which can be related with the difficulty that fishermen have to calculate the weight of zinc replaced every year. The same difficulty was found to obtain data about the paint used for maintenance operations since fishermen usually do not know by heart this type of information. This uncertainty comes from the challenge in obtaining data directly from fishermen, which

is the only way to collect detailed data per vessel as some resources and materials differ from vessel to vessel and there is no official recording.

The gears were the most important item related to eutrophication and mineral resource scarcity. Iron and plastic from gears are important contributors and should be approached whenever freshwater eutrophication or mineral resource scarcity impacts need to be improved. Gears waste management is also a relevant contributor to marine eutrophication. When we analyse plastic losses, the abandoned, lost, or discarded fishing gears (pots and traps) during fishing activities are the main contributors to plastics losses (12.2 g/kg of octopus) and it is higher than for other seafood products assessed in the literature. On average, 67.8 g of plastics (gears, ropes, etc.) per kg of octopus ends up in the waste management system and could generate important losses if they are mismanaged. Waste management of these plastic flows was not extensively studied in this paper but should be assessed in further LCAs focusing on the EoL phase. This study only considers quantity of losses and their destination in the environment. Assessing the associated impacts of micro- and macroplastics on ecosystems is still to be done when applicable characterization models will be available (Woods et al. 2021). It can include, for example, entanglement effects from macroplastics (Woods et al. 2019) or ecotoxic effects from microplastics (Lavoie et al. 2021). This assessment would help to understand the magnitude of impacts associated with plastic emissions and to compare them with other LCIA categories.

Regarding the comparison between traps and pots, it was found that for 1 kg of octopus, more pots are lost than traps, resulting in a higher impact related with plastics pollution to the environment. Nonetheless, vessels using only traps have higher fuel consumption compared to vessels using only pots and the carbon footprint of octopus caught with pots represent half of the value of that found when traps are used. Also, pots have no bycatch or discards, avoiding even juveniles of this species.

4.2 Fishery-specific impact categories

We have presented results for fisheries-specific impact categories addressing seafloor disturbance, sea use, and species removal as these should be used in fisheries LCA (Avadí and Fréon 2015). Without these impacts, seafood from fisheries cannot be fairly assessed since fisheries are based on natural ecosystems that can only function if kept healthy. Currently, there is no stock assessment for common octopus and such initiative will require political will and resources to be allocated. However, management could be improved. For example, a specific management plan could be developed with periodic evaluation of results from each measure to provide detailed information and adjustments needed (Sonderblohm

et al. 2017). Pita et al. (2021) also suggested the use of smaller management areas since they would be more appropriate for local implementation of measures, the development of fishery forecasting, and routine stock assessment to align the fishing effort with the stock status. Finally, a better organization of fishermen and co-management initiatives could improve the fishery management. Even though in Portugal, there is little participation from fishing stakeholders in the decision-making process, this situation is changing, and octopus' fishery in the Algarve could lead to a new management paradigm. Projects concerning the management of the octopus' fishery (e.g. “Tertúlia do Polvo”, during 2014 and 2015) developed participatory workshops with the contribution of representatives from the fishery, governmental agencies, research institutions, and other stakeholders, to promote discussion of management measures and involvement of all parts in the decision-making process (Sonderblohm et al. 2017; Silva et al. 2019). More recently, in 2020, a project was launched (ParticipESCA) with the aim of implementing a co-management framework in the octopus' fishery in the Algarve.

By-catch from traps is not significant, corresponding to 4.3% of the catch, and is absent in pots. Discards are only of octopus under the allowed weight. Therefore, this fishery can be considered very selective, having a low impact in marine life mortality related to non-target species. As a comparison, the discard rate in Moroccan and Mauritania octopus' fishery with trawl is estimated to be 45% (Kelleher 2005). In the Spanish octopus fishing fleet in Mauritania, discards to the sea represent 19.5% of the total catch and skippers report discarding large amounts of Atlantic horse mackerel (*Trachurus trachurus*) due to its low economic value (Vázquez-Rowe et al. 2012). Furthermore, trawls can catch vulnerable species as demersal elasmobranchs, smaller-sized and mostly immature specimens, meaning that they likely have a more detrimental effect.

The seafloor disturbance calculated for octopus' fishery with pots and traps was none since fishing gears do not swept the seafloor. This result is very different when compared with trawling fishery. Bottom trawling collects many different species and causes a negative impact on the seabed, while traps and pots can be considered having little or no physical impact on the seabed (Sauer et al. 2021). In the case of octopus caught with trawl, it results in a seafloor disturbance of an area with 1950 m² per kg of octopus landed (46,800 m² for the FU of 24 kg octopus) (Vázquez-Rowe et al. 2012).

Apart from previous fishery-specific impact categories, we added the MTL and PPR. The results obtained for pots and traps fishery relay on lower impact to the marine ecosystem when compared to fisheries that catch species from higher trophic levels (e.g. demersal fish species). However, it does not require the lowest primary production neither

and therefore species such as small pelagic fish could be a more efficient animal protein than octopus. Having a trophic level 3, octopus are secondary consumers, included in the animals' group that feed on primary consumers, and are mainly carnivorous and predators. Yet, the trophic role of cephalopod species in the food-web is not well-known and it is needed to account not only with their preys but also with their role as prey, as they are part of the diet of various predator species (e.g. cetaceans, seabirds, and large epipelagic fish) (ICES 2013).

4.3 Possible improvements among the octopus' fishery with pots and traps

Portugal has the second octopus' consumption per capita worldwide (1.7 kg per year) (Josupeit 2008), and cephalopods are one of the fastest growing products in the global seafood trade in value and volume (Ospina-Alvarez et al. 2022). Therefore, the global demand for octopus' products is expected to increase as well as the economic-social importance of this fishery in Portugal, and any environmental improvement will have a significant impact on the long-term sustainability of the fishing activity.

The type of progresses that could be implemented in the future to improve the environmental assessment of this octopus fishery is mainly related with fuel consumption, which is indirectly linked with bait used with traps, and gears use. If pots are promoted in relation to traps, the environmental outcome from this fishery would be much lower since the impact for all categories studied is reduced by half (GW, SOD, FE, ME, and FRS), except for ecotoxicity (FET and MET). Pots are a more fuel-efficient capture gear for octopus. However, it would be also important to reduce pots lost and its consequential plastic waste generated in the environment. Some fishermen and Sonderblohm et al. (2017) argued that non-baited pots left at sea can serve as shelters for spawning females and it would turn in a positive consequence to the octopus population. Yet, this was not demonstrated and pots size might not have an internal diameter adequate to properly attach, handle, and ventilate eggs (Sauer et al. 2021). To overcome the problem related with the pots lost and its associated macroplastics generated to the environment, the promotion of ceramic or other type of material less harmful to the environment than plastic could solve part of the problem (e.g. Cátia 2017). In Spain, plastic pots were banned recently (Orden AAA/627/2013) and some fishermen demonstrated concern about the impact of these pots in the ecosystem. Erzini et al. (2008) suggested the replacement of plastic with biodegradable netting and the implementation of a code of conduct leading to less gear loss from gear interaction and theft. An important measure to overcome gears lost is the

compliance with maximum number of gears per boat and signalization to avoid that other fishing gears break the nets employed. These types of measures will be difficult to implement in the current scenario, with low enforcement of management measures. However, the development of a standard, associated with a logo or certification scheme to flag octopus products coming from vessels with transparent procedures and committed with management measures implemented, could discriminate positively vessels devoted to sustainability principles and engage fishermen to a common ground of commitment.

To bridge the lack of evidence related with environmental and economic advantages of using pots vs traps including the use of live vs non-live bait or some materials in the traps, more research is needed to understand which improvements might bring higher benefits for the environment, as well as for the economic return of the activity. Since live bait is based on the exploitation of other species, e.g. green crab, more knowledge is also needed to fully understand the consequences of such a demand increase.

Finally, it is important to highlight that the data collected is limited only to 12% of octopus catches in Algarve and presents a high variability between vessels. Collecting data directly from questionnaires is a difficult task that requires time and persistence to get fishermen confidence. Fishermen usually have support from producers' organizations to deal with accountancy and bureaucracy, and so they often miss detailed records of vessels' consumptions. Furthermore, vessel consumptions and catches can be related with fishermen decisions on the number of gears or its deployment, resulting in different efficiency levels between vessels. To overcome the uncertainty or variability of this type of data, it might be relevant to combine different sources (e.g. interviews and statistics), as done here for FUI data in order to complement a detailed perspective with a broader scenario. Also, due to the fear of disclosing individual procedures or providing specific information that could be used against them later, fishermen may provide information not entirely reliable. As an example, it is very likely that the number of gears lost at sea per year obtained from the questionnaires is underestimated due to distrust of fishermen to give this type of information. Still, considering that on average, each vessel loses 372 pots and 234 traps annually and for Algarve in 2019, there were issued 189 pot and 326 trap licenses (Pita et al. 2021), the overall result of gears lost can be around 70,308 pots and 76,284 traps, resulting in an estimation of 279 tonnes of plastic, concrete, and iron are dumped each year to the marine ecosystem. The results presented are a first attempt to assess flows in a systematic way by using LCA methodology to add a broader perspective of fishing operations and show where higher potential exist for improvements.

5 Conclusions

The environmental assessment of common octopus' fishery with pots and traps in the Algarve showed that few resources are needed and contributions are light to the environmental impact categories selected. Apart from fuel, which is the dominant contributor to global warming, it was found that zinc together with gears' materials production and waste were the main contributors to eutrophication and toxicity impacts, respectively. Pots and traps are a highly selective fishing gear, causing negligible disturbance to the seafloor. The common octopus' stock is not assessed, which enhances uncertainty about the state of the fishing resource on the long term, but management measures exist and could be enforced. Primary production required is not very high, but octopus' trophic level is not the lowest neither since they are considered carnivores or predators. Nonetheless, a drawback exists related with the number of gears lost in the environment and potential rubbish continuously released to the marine ecosystem. A problem that could be improved with more surveillance, higher commitment from fishermen to support management measures, and further knowledge about environmental impacts from fishing operations.

Even though pots and traps are usually considered a unique fishing métier by authorities, and in most reports or research studies they are assessed together, they are different with regard to environmental impacts (pots have lower fuel consumption and generate octopus with lower carbon footprint). Further studies could help to understand if differences found in this study between pots and traps are confirmed with a larger sample or in a different region. It would also be relevant to have more evidences if benefits (economical and environmental) exist when using traps with non-live bait. This could clarify the assumption that measures applied only in Algarve are effective to regulate the fishing effort or if other measures would be more adequate.

The common octopus caught with pots and traps presented a low carbon footprint when compared to other type of seafood products, especially to common octopus caught with trawl. It represents a typical case where the fishing gear is more important than the species when assessing environmental impacts from seafood products. Trawling is more destructive to the marine ecosystem than pots and traps fishery, has higher level of discards, can severely damage benthonic communities, and represents higher fuel consumption per FU resulting in a higher carbon footprint for those octopus' products. Although pots and traps caught octopus would be a preferred alternative from the environmental point of view, often producers and consumers are not aware of such differences. Identifying

the capture method may be difficult at certain circumstances, for example eating out-of-home (e.g. restaurants), but more highlight should be put on the environmental outcomes from different fishing gears to promote more informed choices for consumers.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-022-02072-7>.

Acknowledgements We would like to thank all those in the octopus' fishery with traps and pots in Algarve who have patiently helped us in explaining, supplying, and verifying data, especially the fishermen that were available to participate in the interviews (Afonso, Arlindo Correia, Beto, Carlos Janota, Carlos Leal, Dário, David Mestre, Domingos, Eduardo Andrés, Francisco, Herculano Santana, João Barreto, João Vieira, José Agostinho, José David, José Ferreira, Manuel Madeira, Marco Pereira, Paulo Molina, Pedro Correia, Vítor Martins) and representatives of associations and producers' organizations (Sónia Olim, Ana Rita Boto, Miguel Cardoso). We are also most grateful for fruitful conversations and helpful suggestions from researchers and representatives of organizations that work or have been studying the octopus' fishery in Portugal (Carlos Sonderblohm, Sílvia Lourenço; David Piló, Rita Sá, Francisco Leitão).

Funding This work was supported by the NEPTUNUS project (EAPA_576/2018).

Data availability The datasets generated and/or analysed during the current study are included in this published article and its supplementary information file and are also available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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