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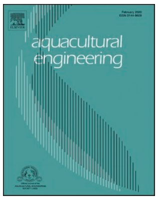

Insights into different marine aquaculture infrastructures from a life cycle perspective

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ABSTRACT

Aquaculture facilities represent an often-neglected process in environmental impact studies. This study focus on the environmental impact assessment of alternative net materials in Mediterranean marine aquaculture. A Life Cycle Assessment was conducted using primary and secondary data from specific databases and literature. Three baseline scenarios were compared: copper alloy net cages with 100 % of recycled material (CAN100), 75 % of recycled material (CAN75), and polyethylene net (PEN) System boundaries include manufacturing and disposal of cages, nets, and mooring system. The use and emissions of antifouling paints and CAN were considered. Sensitivity analysis of the most impacting sub-processes and Uncertainty analysis were also conducted. The use of CAN is advantageous in terms of environmental impact, but only considering a complete recyclability of the net at the end of its service life. Moreover, when considering a reduced service life of the PEN due to the detrimental effect of biofouling, the advantage of the CAN is even more evident. To counteract the negative effect of biofouling, copper-based antifouling paints are generally used in marine aquaculture. These products are a main environmental hotspot in PEN systems. Therefore, a higher consumption of such products could determine an environmental burden shifting from CAN to PEN ones. So far, CAN are not widespread in the aquaculture industry, mainly due to the high cost of initial investment compared to traditional PEN. Considering operational and environmental advantages, CAN cages could represent an affordable and resilient solution for aquaculture enhancing environmental, economic, and social performances of this industry.

1. Introduction

Aquaculture is the production, under controlled conditions, of freshwater or saltwater aquatic organisms for human consumption and non-food use. The growth of the aquaculture industry has been astonishing in the last 50–60 years and is known as 'blue revolution' (Carballeira Braña et al., 2021). Modern aquaculture production started during the 1960s in Asia and between 1970s and 1980s in Western countries and has grown at an average of 7.5 % per year since 1970 because of the increasing demand for fish proteins and the stagnation or even the decrease in capture fisheries (FAO, 2022). Historically dominated by extensive and improved-extensive pond-based farming systems sometimes supplemented with agricultural by-products, aquaculture production has been increased shifting toward intensive systems, which rely on the use of pelleted feed in marine, brackish-water, and freshwater environments (Henriksson et al., 2021).

Aquaculture production reached a record of more than 122 million metric tons in 2020 mostly represented by finfish production (46.9 % of total) followed by algae (28.6 % of total) and molluscs (14.5 % of total) (FAO, 2022). Aquaculture is mostly practiced in monoculture, i.e., using sea cages, tanks, ponds, or recirculating aquaculture systems (RASs) to produce a single species (Thomas et al., 2021). Marine farms consist of several floating cages in which fish are raised from juveniles up to commercial size; all operations (e.g., feeding, maintenance) are conducted by highly skilled personnel with service boats (Cardia and Lovatelli, 2015). Several other activities are conducted on land, such as post-harvesting operations and processing, and feed storage, among others (Zoli et al., 2023a). In the Mediterranean area, coastal marine farms represent the predominant aquaculture production, representing more than 95 % of the production of seabass and seabream (Zoli et al.,

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2023a).

Despite the importance of aquaculture for food production, concerns related to its expansion have been highlighted (Naylor et al., 2000). Some of the environmental concerns associated with aquaculture are feed production and the release of nutrient-rich effluents in the surrounding environment due to animal metabolism (Thomas et al., 2021).

The environmental sustainability of products, processes, or services is often assessed using the Life Cycle Assessment (LCA), which is a methodology defined by standards ISO 14040 and 14044 (ISO, 2006a, 2006b) to quantify the potential environmental impact on ecosystems, human health, and natural resources caused by products and systems throughout their entire life cycle (Cucurachi et al., 2019). Many examples of LCA application in the aquaculture sector are available in the literature (Zoli et al., 2023a) referring both to fish production (Abdou et al., 2017; Zoli et al., 2023b), shellfish production (Martini et al., 2022), or alternative farming systems such as integrated multi-trophic aquaculture (Chary et al., 2020; Mendoza Beltran et al., 2018), recirculating aquaculture systems (Aubin et al., 2006), and aquaponics (Jaeger et al., 2019; Körner et al., 2021). However, infrastructures are often neglected components in aquaculture LCA studies (Bohnes et al., 2019) or fragmented and non-exhaustive inventories are provided for them (Zoli et al., 2023a). The role of infrastructures in the environmental impact of aquaculture facilities is generally lower than those of feed, energy carriers, and nutrient emissions from fish metabolism. In the review conducted by Bohnes and Laurent (2019) 33 studies out of 65 studies analysed included infrastructures and 25 of them conducted a contribution analysis. The reason stated by the authors for not including these stages are the expected reduced impacts or the lack of primary data and available databases for a consistent modelling (Bohnes et al., 2019). Nevertheless, infrastructures accounted for at least 5 % of the impact in at least one impact category (IC) (Bohnes and Laurent, 2019).

In the study of Aubin et al. (2009), the infrastructures for European sea bass farming in Greece contributed to energy use (9 % of the overall impact), climate change (8 %), and acidification (6 %) for the production of 1 metric tons of fish. Abdou et al. (2017) reported an impact associated with infrastructures on global warming, land occupation, and total cumulative energy demand for European sea bass and gilthead sea bream, in all the impact categories considered the impact resulted negligible (0.3–0.05 % of the overall impact). García et al. (2016), reported a detailed inventory of sea cages used for 1 metric tons of gilthead sea bream production in Spain. The impact of facilities resulted generally low except for acidification (26 % of the overall impact) which could be mostly associated with the mooring system (García et al., 2016).

Thus, considering the importance of such component, infrastructures should by default be included in LCA of aquaculture systems. (Bohnes et al., 2019). Moreover, expanding knowledge and deeply investigating the contributions of infrastructure is particularly relevant considering their larger influence on agriculture processes than industrial ones (Henriksson et al., 2012). In marine aquaculture, the infrastructures relating to the farming phase perform the function of containment of the farmed animals and prevent the intrusion of predators. These performances must be guaranteed along the whole production cycle. The design of marine aquaculture infrastructure should therefore consider the local hydrodynamic and biological conditions (e.g. biofouling). Periodic maintenance the effectiveness of the infrastructure. When modelling marine aquaculture infrastructures, the materials necessary for their construction, the maintenance phase (including the use of boats), and the disposal of materials at the end of their life should therefore be considered. The presence of containment structures is one of the elements that differentiates aquaculture from fishing. In the case of industrial fishing, the infrastructure element is substantially limited to boats and fishing equipment. Raw material inputs are therefore usually considered both during construction and maintenance (e.g. antifouling paints for boat hulls). Vázquez-Rowe et al. (2012) listed the most relevant data required for a proper life cycle inventory in of wild fish capture systems which include gear production and use (including gear loss, i.e., “ghost nets”, and anti-fouling and boat paint).

Biofouling is one of the major concerns in marine aquaculture infrastructures (Fitridge et al., 2012). It changes the flow field around the cages, reduces water exchange across the nets, decreases the availability of dissolved oxygen and affects the current/wave-induced forces acting on and deforming the structure (Fitridge et al., 2012; Nobakht-Kolur et al., 2021). Because of the reduction of water circulation inside the cage, the onset of parasites and pathogens infecting farmed fish is increased (Paladini et al., 2017). These negative impacts on fish health and welfare lead farmers to increase the use of chemicals and chemotherapeutants to cope with resulting slower fish growth rates and higher feed conversion rates (Ayer et al., 2016). Polymer nets are also subject to mechanical fatigue which is enhanced by the added weight of biofouling and attempts by marine predators to hunt fish contained in the nets (Jackson et al., 2015). Thus, mesh net management plays a crucial role in optimising aquaculture yields and reducing impacts. Considering the relative short lifespan compared to other components, the interventions required to maintain optimal performances of the net in terms of water exchange and fish escapees or predator intrusion include periodical washing, the application of antifouling paints (AFP), deployment of divers to clean the nets, and periodic replacement (Fitridge et al., 2012). The most common AFP used in aquaculture is copper-based coating which is applied directly to nets to prevent biofouling (Kalantzi et al., 2016). Consequently, the active ingredients in these paints leach into the water and may exert toxic effects on local marine organisms both in the water column and the sediments below the cages, where the chemicals tend to accumulate (Burridge et al., 2010).

Copper alloy nets (CAN) offer some advantages in this context. The construction of nets with copper-zinc, copper-nickel, and copper-silicon alloys may prevent biofouling (Chambers et al., 2012), improve fish health and welfare (González et al., 2013), prevent the loss of fish through escapes and predator attack (Moe et al., 2009), resist corrosion, ripping, and degradation, and require less cleaning and diver maintenance (González et al., 2013). Moreover, in a comparative LCA study of two salmon farms in which the authors compared the use of CAN and conventional nylon nets, the environmental performance of salmon production appeared improved by using CAN (Ayer et al., 2016). Furthermore, these materials have peculiar hydrodynamic properties and structural characteristics, such as the maintenance of their shape against waves and currents, which make them suitable for use in both off-shore and in-shore mariculture (Cha et al., 2013; González et al., 2013). In addition, copper-alloy can be recycled at the end of the use phase, thus contributing to reduce the consumption of virgin material for CAN production (Ayer et al., 2016). However, the need for a specific design for such nets and higher initial costs limited the use of these solutions (Drach et al., 2016). Although the oligotrophic nature of Mediterranean Sea (Tičina et al., 2020), several coastal areas, where mariculture facilities are generally located, receive loads of nutrients from different inputs, resulting in more eutrophic conditions (Karydis and Kitsiou, 2012). In this context, the use of CAN technology would contribute to extend marine aquaculture infrastructure service life compared to traditional polyethylene net (PEN) systems.

2. Materials and methods

2.1. Goal and scope definition

In the present study, two netting materials for aquaculture sea cages were compared in terms of environmental performance. In particular, CAN cages compared to traditional PEN cages for Mediterranean aquaculture. Therefore, different scenarios have been evaluated using LCA. In particular: i) the amount of CAN recycled, ii) the lifespan of CAN and PEN cages; iii) the reduction in AFP in PEN cages, and iv) different AFP.

Primary data were obtained from a pilot farm located in the

Mediterranean Sea (Capraia, Italy) and companies specialised in marine aquaculture facility construction. Aquaculture infrastructures confine the rearing environment of fish preventing escapees of farmed animals or intrusion of external individuals or predators while maintaining adequate rearing conditions for fish. Moreover, they should keep unaltered those functions over their whole life cycle. Therefore, the functional unit chosen was 1 metric ton of fish produced over the lifespan of the net. The fish production considered was 56.25 metric tons cage^{-1} y^{-1}, obtained by dividing a production of 1800 metric tons y^{-1} by 32 cages (Zoli et al., 2023b). System boundaries (Fig. 1) include all the processes related to fish cage and mooring system, manufacturing, and disposal. Moreover, emissions from CAN and AFP during cage's lifespan was included. All other inputs commonly considered in LCA studies of fish aquaculture were excluded (i.e., feed production, juveniles' production, routinary operations, fleet, etc.) as the study focused on infrastructures. The novelty of the study is represented by the strict focus on marine aquaculture infrastructures, notably floating collar sea cages commonly used in Mediterranean area. Moreover, while the benefit of using CAN has been highlighted in other studies, a comprehensive LCA study on this innovative technological solution was only conducted on Atlantic salmon farming in Chile. This study is aimed at researchers and practitioners in the Mediterranean aquaculture sector interested in evaluating alternative technological solutions to common marine aquaculture infrastructures.

2.2. Life cycle inventory

For both CAN and PEN systems primary data were used. Data were provided by companies specialized in fish farming infrastructures. Data were referred to one cage of 12 m of diameter. Input data were then upscaled using reference for aquaculture cages construction (Cardia and Lovatelli, 2015) up to 30 m diameter, which is the common size found in open water aquaculture systems in Italy. The mooring system was modelled according to design specifications (Cardia and Lovatelli, 2015). The mooring system was common between both farming infrastructure solutions. The amount of each component is reported in Table 1.

The two infrastructures had different components. The CAN cage (Fig. 2) was considered made of recycled material by 75 % (CAN75), while the remaining fraction was composed of virgin material. The alloy used in the present modelling was made of 70 % copper and 30 % zinc. Due to the higher weight of the CAN cage, an additional floating ring was required, while no sinker was considered in this type of cage. Jump and bird net are made by PE. In the PEN cage both the underwater net,

Table 1
Inventory of copper alloy net and polyethylene net cages baseline scenarios. Values referred 1 metric ton of fish produced during net service life.

Component	Service life (years)	Material	Unit	CAN	PEN
Floating collar	20	HDPE pipes	kg	15.10	20.68
		PES floating material	kg	0.56	0.56
		Ropes	kg	-	0.63
		Chains, metal components	kg	-	4.98
Mooring system	20	Ropes	kg	1.57	2.35
		Anchors, metal components	kg	8.06	12.09
		PES floating material	kg	0.28	0.43
PE N[1]	4	PE mesh	kg	0.41	2.18
CAN	6	Cu Zn alloy mesh	kg	38.24	
AFP	n/a	Cu-based AFP	kg		1.65
Emission					
Cu	n/a	n/a	kg	96.27	-
Zn	n/a	n/a	kg	82.52	-
AFP	n/a	n/a	kg	-	1.09

Legend: AFP, antifouling paint; CAN, copper-ally net; PEN, polyethylene net. [1] A part of PEN is required also for CAN system as jump and anti-predator net.

Fig. 2. A 12 m-cage used as a reference for copper alloy net (CAN) system.

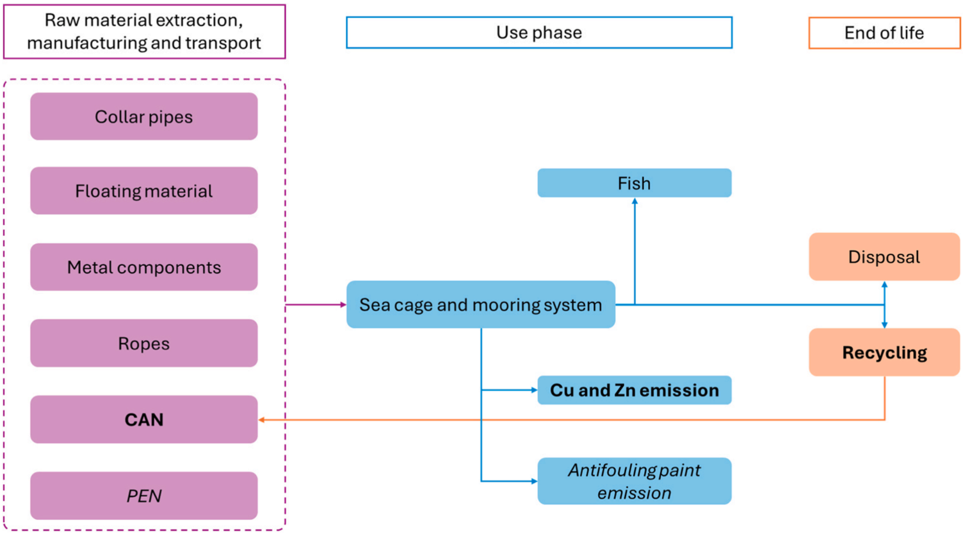

Fig. 1. System boundaries of the considered system. Bolded items refer to copper alloy net (CAN) system, while italic items refer to polyethylene net (PEN) system.

jump, and bird net were made of PE. Moreover, PEN cages required a sinker made of high-density polyethylene (HDPE), metal chains, several connectors, and ropes. The lifespan of PEN cages was considered 4 years, according to expert opinion. For CAN cages a lifespan of 6 years was considered (Ayer et al., 2016). For the mooring system and other components of both systems, a lifespan of 20 years was considered (Ayer et al., 2016). The CAN recyclability was considered as the avoided impact associated with virgin metal requirement.

The AFP was modelled considering the commercial product specifications. A single application of AFP was considered in the PEN system. Therefore, no further applications of AFP were considered during the service life of the PEN.

Emissions were considered for both netting materials. In the CAN system, Cu and Zn emissions were considered as 7 μg cm^{-2} d^{-1} and 6 μg cm^{-2} d^{-1}, respectively (Ayer et al., 2016). While emissions from AFP were modelled as 2/3 of AFP components over the whole life cycle, as considered in Agribalyse (Auberger et al., 2022). The components considered emitted from the AFP were: copper oxide, petroleum naphta used as solvent, xylene, kaolin, and zinc.

Background data regarding input materials, manufacturing, transport, and disposal were obtained from databases Ecoinvent 3.8 and Agribalyse 3.1. In particular, Ecoinvent was used as database for all the raw materials used in the modelling of both CAN and PEN cages. Agribalyse was used only for the alternative AFP used for the sensitivity analysis (see section 2.4). The list of all the background processes used is provided as supplementary material.

2.3. *Life cycle impact assessment and result interpretation*

The following impact categories (IC) were calculated using EF 3.0 V1.03 (Fazio et al., 2019). Moreover, total cumulative energy demand (TCED) was calculated as reported in (Abdou et al., 2017). The list of all the ICs considered is provided in Table 2. The software used for the analysis was Simapro V.9.3.

Contribution analysis was carried out to determine the most relevant phases for the environmental impact. The overall impact was divided into six relevant stages as follow: i) mooring system manufacturing and disposal, ii) collar pipes manufacturing and disposal, iii) PEN manufacturing and disposal, iv) CAN manufacturing and disposal, v) AFP manufacturing and emissions, and vi) emissions of Cu and Zn from CAN cage.

Sensitivity analysis was conducted by varying relevant parameters of both farming solutions. In particular, the following inputs were changed: i) the amount of CAN recycled at the end of net lifespan was increased from 75 % to 100 % (CAN100), ii) the lifespan of both farming solutions was increased and reduced by 20 %, iii) the consumption of AFP was increased and reduced by 20 %, iv) a different AFP product and related emissions available on Agribalyse database was used. Data regarding sensitivity analysis are reported in Table 3 and 4 as positive and negative values represent the percentage increase and decrease compared to the baseline scenario, respectively. Absolute values are reported in supplementary material. The results of the sensitivity analysis as absolute impact is provided as supplementary material. An uncertainty analysis was conducted comparing the environmental impact on two baseline scenarios each time (i.e., PEN vs CAN75, PEN vs CAN100, and CAN75 vs CAN100). The analysis has been repeated using the most up to date version of EF method (i.e., EF 3.1 v 1.0) as characterization factors for some metals including Cu has been drastically revised (Andreasi Bassi et al., 2023).

Table 2
List of all the impact categories considered and relative units.

Impact category	Acronym	Unit
Climate change	CC	kg CO2 eq
Ozone depletion	OD	kg CFC11 eq
Ionizing radiation	IR	kBq U−235 eq
Photochemical ozone formation	OF	kg NMVOC eq
Particulate matter	PM	disease inc.
Human toxicity, non-cancer	HT-nc	CTUh
Human toxicity, cancer	HT-c	CTUh
Acidification	AC	mol H+ eq
Eutrophication, freshwater	FE	kg P eq
Eutrophication, marine	ME	kg N eq
Eutrophication, terrestrial	TE	mol N eq
Ecotoxicity, freshwater	Feco	CTUe
Land use	LU	Pt
Water use	WU	m3 depriv.
Resource use, fossils	RU-f	MJ
Resource use, minerals and metals	RU-mm	kg Sb eq
Total cumulative energy demand	TCED	MJ eq

3. Results

The worst scenario is always CAN75, where a part of virgin material is still required (Table 3). The scenarios CAN100 and PEN showed lower impacts in most of the ICs considered. In terms of CC, the PEN scenario showed a lower (-0.8 %) environmental footprint (50.72 kg CO2 eq) compared to CAN100 (51.15 kg CO2 eq), as well as for OD (-23.7 %), IR (-18.6 %), Feco (-146.8 %), WU (-86.7 %) (Table 3). The other impact categories, including TCED (12.4 %), LU (21.7 %), AC (53.2 %), FE (39.8 %), ME (18.5 %), and TE (28.3 %) showed a higher impact in PEN than in the CAN100 system (Table 3).

Contribution analysis (Fig. 3) showed that in the CAN cage, the share of environmental impact changed according to the amount of virgin metal used. In the CAN100 (Fig. 3**a**), the most impactful processes were CAN and collar pipes manufacturing and disposal. Manufacturing and disposal of CAN accounted for an average impact in all the ICs considered of 32.4 % with a minimum of 4.3 % (Feco) and a maximum of 68.3 % (WU). Collar pipes manufacturing and disposal accounted for 30.3 % of impacts on average, ranging from 2.9 % (Feco) and 63.3 % (OD). On the contrary, when CAN is composed of 25 % of virgin metal (Fig. 3**b**), CAN manufacturing, and disposal represented 83.9 % of the impacts on average. The lowest impact is associated to OD (53.8 %) while the highest impact is for RU-mm (99.8 %). In the PEN system

Table 3
Comparison of environmental impacts of copper alloy net cages with 100 % of recycled material (CAN100), 75 % of recycled material (CAN100), and polyethylene net (PEN).

Impact category	Unit	CAN100	CAN75	PEN
Climate change	kg CO2 eq	51.15	104.61	50.72
Ozone depletion	kg CFC11 eq	4.27×10^{-6}	7.31×10^{-6}	3.45×10^{-6}
Ionising radiation	kBq U−235 eq	3.33	10.16	2.81
Photochemical ozone formation	kg NMVOC eq	0.13	0.87	0.16
Particulate matter	disease inc.	2.06×10^{-6}	1.08×10^{-5}	2.57×10^{-6}
Human toxicity, non-cancer	CTUh	1.49×10^{-6}	5.31×10^{-5}	2.97×10^{-6}
Human toxicity, cancer	CTUh	1.12×10^{-7}	8.37×10^{-7}	1.17×10^{-7}
Acidification	mol H+ eq	0.16	4.00	0.34
Eutrophication, freshwater	kg P eq	0.02	0.32	0.03
Eutrophication, marine	kg N eq	0.04	0.23	0.04
Eutrophication, terrestrial	mol N eq	0.33	3.04	0.46
Ecotoxicity, freshwater	CTUe	5723.75	37490.84	2319.37
Land use	Pt	164.42	1456.95	209.94
Water use	m3 depriv.	37.46	104.36	20.06
Resource use, fossils	MJ	711.23	1374.47	820.86
Resource use, minerals and metals	kg Sb eq	2.95×10^{-4}	9.58×10^{-2}	4.65×10^{-3}
Total cumulative energy demand	MJ eq	808.53	1688.92	922.71

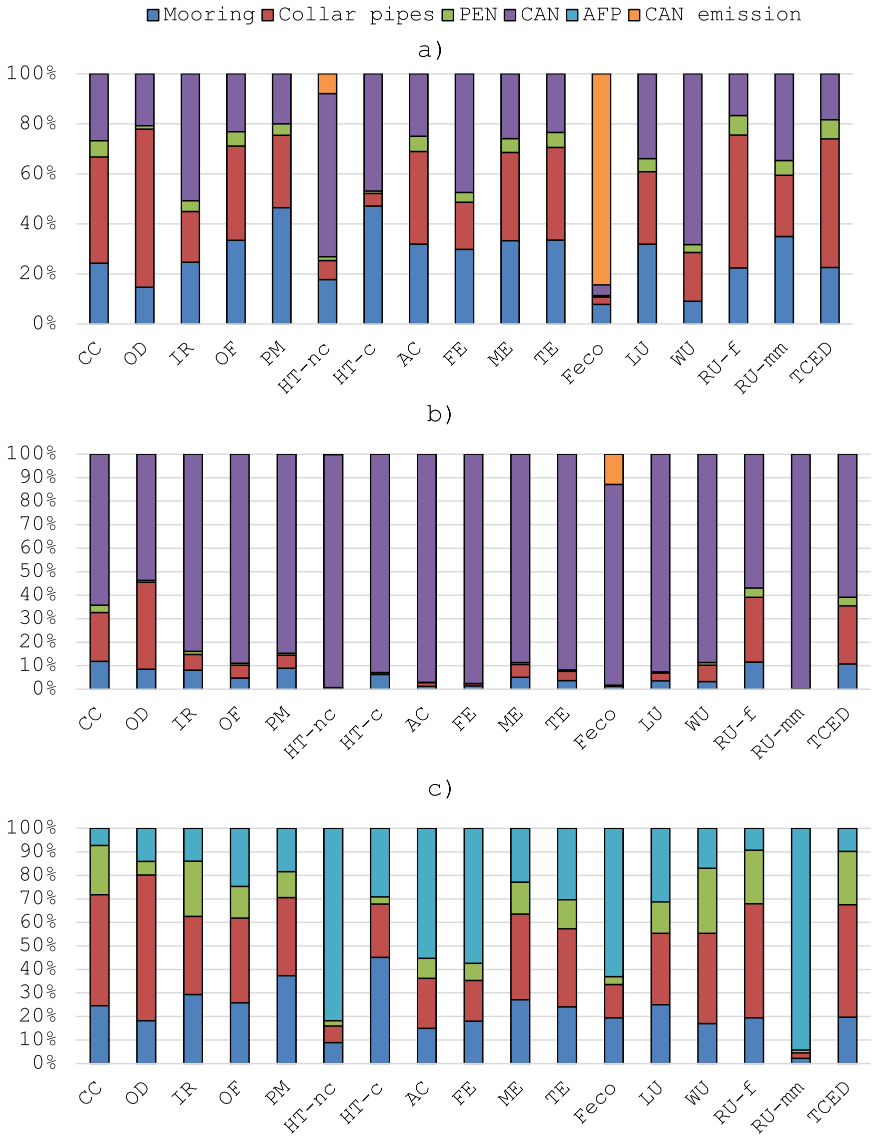

Fig. 3. Contribution analysis of different system components for a) copper alloy net (CAN) cages with 100 % of recycled material, b) CAN with 75 % of recycled material, and c) polyethylene net for the following impact categories: climate change (CC), ozone depletion (OD), ionizing radiation (IR), photochemical ozone formation (OF), particulate matter (PM), human toxicity, non-cancer (HT-nc), human toxicity, cancer (HT-c), acidification (AC), eutrophication, freshwater (FE), eutrophication, marine (ME), eutrophication, terrestrial (TE), ecotoxicity, freshwater (Feco), land use (LU); water use (WU), resource use, fossils (RU-f), resource use, minerals and metals (RU-mm), and total cumulative energy demand (TCED).

(Fig. 3**c**), the major source of impact was the use and emissions associated with AFP which accounted for 34.1 % of impact for all the ICs considered, ranging from 7.2 % (CC) and 94.2 % (RU-mm). With respect to the AFP, the majority of the impact resulted from the manufacturing of AFP rather than emissions to the water. Also, manufacturing and disposal of collar pipes accounted for a significant share of environmental impacts (31.3 %) with a lowest impact for RU-mm (2.3 %) and the highest impact for OD (62.1 %).

As expected, by increasing the lifespan of the netting system by 20 %, the environmental impact decreased compared to baseline scenarios (Table 4). On the contrary, by reducing the lifespan of the netting system the overall impact increased compared to baseline scenarios (Table 4).

In the PEN scenarios, the most affected ICs were RU-mm (23.9 %), HT-nc (21.0 %), Feco (16.6 %), FE (16.2 %), and AC (15.9 %), while a reduced effect was observed for OD (4.9 %), CC (7.0 %), PM (7.4 %), RU-f (8.0 %), and HT-c (8.1 %). In the CAN 75 % REC scenarios, the reduction of the impact associated with extended lifespan was greater for RU-mm (24.9 %), HT-nc (24.8 %), FE (24.4 %), AC (24.2 %), and HT-c (23.2 %), while the less affected ICs were: OD (13.4 %), RU-f (14.2 %), TCED (15.2 %), CC (16 %), and IR (21.0 %). In the scenarios modelled for CAN100 % REC, the ICs with a higher impact reduction were WU (17.1 %), HT-nc (16.3 %), IR (12.7 %), FE (11.8 %), and HT-c (11.7 %), while the effect of increased lifespan was less evident in Feco (1.1 %), RU-f (4.2 %), TCED (4.6 %), PM (5.0 %), and OD (5.2 %).

As AFP is one of the main processes contributing to the environmental impact in PEN cages, a further scenario was evaluated to assess the effects on the environmental impacts of the reduction and increase of AFP use by 20 % (Table 5).

Moreover. a different background process was used to compare environmental results. By increasing the consumption of AFP. the highest increases in environmental impact compared to the baseline scenario were observed for AC (11.1 %). FE (11.5 %). Feco (12.6 %). HT-nc (16.4 %). and RU-mm (18.8 %). while CC. RU-f. TCED. OD. and IR increased by 1.4–2.8 %. When using a different AFP paint. the results for some ICs increased drastically compared to the baseline scenario: FE (85.9 %). HT-nc (47.6 %). ME (31.3 %). and LU (21.7 %). On the other

Table 4
positive and negative variation of nets' lifespan (LS) by 20 % in copper alloy with 100 % (CAN100) and 75 % (CAN75) of recycled material and polyethylene net (PEN) cages. The positive and negative values represent the percentage increase and decrease compared to the baseline scenario (Table 3), respectively.

Impact category	CAN100	CAN100	CAN75	CAN75	PEN	PEN
	-20 % LS	+20 % LS	-20 % LS	+20 % LS	-20 % LS	+20 % LS
Climate change	6.7 %	−4.5 %	16.0 %	−10.7 %	7.0 %	−4.7 %
Ozone depletion	5.2 %	−3.5 %	13.4 %	−8.9 %	4.9 %	−3.3 %
Ionising radiation	12.7 %	−8.5 %	21.0 %	−14.0 %	9.3 %	−6.2 %
Photochemical ozone formation	5.8 %	−3.9 %	22.2 %	−14.8 %	9.5 %	−6.4 %
Particulate matter	5.0 %	−3.3 %	21.2 %	−14.1 %	7.4 %	−4.9 %
Human toxicity, non-cancer	16.3 %	−10.9 %	24.8 %	−16.5 %	21.0 %	−14.0 %
Human toxicity, cancer	11.7 %	−7.8 %	23.2 %	−15.5 %	8.1 %	−5.4 %
Acidification	6.2 %	−4.1 %	24.2 %	−16.2 %	15.9 %	−10.6 %
Eutrophication, freshwater	11.8 %	−7.9 %	24.4 %	−16.3 %	16.2 %	−10.8 %
Eutrophication, marine	6.5 %	−4.3 %	22.1 %	−14.8 %	9.1 %	−6.1 %
Eutrophication, terrestrial	5.9 %	−3.9 %	22.9 %	−15.3 %	10.7 %	−7.1 %
Ecotoxicity, freshwater	1.1 %	−0.7 %	21.3 %	−14.2 %	16.6 %	−11.1 %
Land use	8.5 %	−5.7 %	23.1 %	−15.4 %	11.2 %	−7.4 %
Water use	17.1 %	−11.4 %	22.2 %	−14.8 %	11.2 %	−7.4 %
Resource use, fossils	4.2 %	−2.8 %	14.2 %	−9.5 %	8.0 %	−5.3 %
Resource use, minerals and metals	8.7 %	−5.8 %	24.9 %	−16.6 %	23.9 %	−15.9 %
Total cumulative energy demand	4.6 %	−3.1 %	15.2 %	−10.2 %	8.1 %	−5.4 %

Table 5
Environmental impact of polyethylene net cages (PEN) increasing and reducing the antifouling paint (AFP) consumption by 20 % and using a different antifouling paint (Agribalyse). The positive and negative values represent the percentage increase and decrease compared to the baseline scenario (Table 2), respectively.

Impact category	-20 % AFP	+20 % AFP	AFP Agribalyse	-20 % AFP Agribalyse	+20 % AFP Agribalyse
Climate change	−1.4 %	1.4 %	2.9 %	0.9 %	5.0 %
Ozone depletion	−2.8 %	2.8 %	−3.9 %	−5.9 %	−1.9 %
Ionising radiation	−2.8 %	2.8 %	−3.6 %	−5.6 %	−1.5 %
Photochemical ozone formation	−4.9 %	4.9 %	−0.9 %	−5.7 %	3.8 %
Particulate matter	−3.7 %	3.7 %	3.5 %	−0.8 %	7.9 %
Human toxicity. non-cancer	−16.4 %	16.4 %	47.6 %	21.7 %	73.5 %
Human toxicity. cancer	−5.8 %	5.8 %	−11.6 %	−15.1 %	−8.1 %
Acidification	−11.1 %	11.1 %	1.6 %	−9.8 %	13.0 %
Eutrophication. freshwater	−11.5 %	11.5 %	85.9 %	57.3 %	114.6 %
Eutrophication. marine	−4.6 %	4.6 %	31.3 %	20.5 %	42.2 %
Eutrophication. terrestrial	−6.1 %	6.1 %	4.0 %	−2.9 %	10.8 %
Ecotoxicity. freshwater	−12.6 %	12.6 %	−4.6 %	−16.3 %	7.1 %
Land use	−6.2 %	6.2 %	21.7 %	11.1 %	32.3 %
Water use	−3.4 %	3.4 %	5.4 %	1.0 %	9.9 %
Resource use. fossils	−1.9 %	1.9 %	−2.1 %	−3.6 %	−0.7 %
Resource use. minerals and metals	−18.8 %	18.8 %	−77.3 %	−80.7 %	−73.9 %
Total cumulative energy demand	−2.0 %	2.0 %	−0.7 %	−2.5 %	1.1 %

hand. other ICs showed a reduced impact. in particular RU-mm (-77.3 %). HT-c (-11.6 %). and Feco (-4.6 %).

A sensitivity analysis was conducted using the method EF3.1 (Table 6). The results were consistent with those obtained using EF3.0 except for the following ICs: OD. HT-nc. Feco. WU. and RU-mm which showed a considerable difference compared to the previous method.

Table 6
Comparison of environmental impacts of copper alloy net cages with 100 % of recycled material (CAN100). 75 % of recycled material (CAN100). and polyethylene net (PEN) using the Life Cycle Impact Assessment method Environmental Footprint 3.1.

Impact category	Unit	CAN100	CAN75	PEN
Climate change	kg CO2 eq	50.25	104.78	50.02
Ozone depletion	kg CFC11 eq	3.00 ×10–6	3.66 ×10–6	1.98 ×10–6
Ionising radiation	kBq U−235 eq	3.08	9.86	2.50
Photochemical ozone formation	kg NMVOC eq	0.14	0.92	0.18
Particulate matter	disease inc.	2.12 ×10–6	1.11 ×10–5	2.65 ×10–6
Human toxicity, non-cancer	CTUh	4.65 ×10–7	5.18 ×10–5	2.83 ×10–6
Human toxicity, cancer	CTUh	1.08 ×10–7	7.22 ×10–7	1.07 ×10–7
Acidification	mol H+ eq	0.16	4.01	0.34
Eutrophication, freshwater	kg P eq	0.02	0.32	0.03
Eutrophication, marine	kg N eq	0.04	0.24	0.04
Eutrophication, terrestrial	mol N eq	0.33	3.10	0.46
Ecotoxicity, freshwater	CTUe	236.42	5774.68	358.90
Land use	Pt	152.27	1407.77	196.87
Water use	m3 depriv.	29.62	91.09	12.51
Resource use, fossils	MJ	707.77	1394.02	821.69
Resource use, minerals and metals	kg Sb eq	2.12 ×10–4	5.31 ×10–2	2.51 ×10–3

The uncertainty analysis (Fig. 4) showed the probability that the environmental impact of one cage system resulted lower (left bars) or equal or higher (right bars) than the other. The comparison among CAN100 and PEN (Fig. 4**a**) showed that the environmental impact is always higher in the PEN system except for the categories OD. IR. and Feco which showed the opposite trend. The ICs HT-nc and HT-c showed the highest uncertainty. Also CC and WU showed a high uncertainty with a probability of the impact in PEN being higher than those in CAN100 of 64 % and 53 %. respectively. The comparison between CAN75 and PEN (Fig. 4**b**) showed that the environmental impact of the CAN75 resulted higher in all the ICs considered. The only exception was represented by the ICs HT-nc. HT-c. and WU which showed a probability close to 50 % of a higher impact in the PEN system than in the CAN75. A similar trend was observed for the comparison of CAN100 and CAN75 (Fig. 4**c**). which confirm the higher impact of CAN75 in all the ICs considered. As for the other comparisons. a high uncertainty was associated with the ICs HT-nc. HT-c. and WU.

Fig. 4. uncertainty analysis showing the probability that the environmental impact of copper alloy net cages with 100 % of recycled material (CAN100). 75 % of recycled material (CAN100). and polyethylene net (PEN) resulted lower (left bars) or equal or higher (right bars) than the other. climate change (CC). ozone depletion (OD). ionizing radiation (IR). photochemical ozone formation (OF). particulate matter (PM). human toxicity. non-cancer (HT-nc). human toxicity. cancer (HT-c). acidification (AC). eutrophication. freshwater (FE). eutrophication. marine (ME). eutrophication. terrestrial (TE). ecotoxicity. freshwater (Feco). land use (LU); water use (WU). resource use. fossils (RU-f). resource use. minerals and metals (RU-mm). and total cumulative energy demand (TCED).

4. Discussion

The use of CAN compared to traditional PEN could lead to a reduction of environmental impact associated with infrastructures in marine aquaculture farms. However, the use of CAN could be advantageous only when a complete recyclability of the nets would be achieved at the end of their service life. The adoption of CAN with 100 % recyclability has on average comparable impacts to PEN systems, but specifically, some impact categories are significantly improved. The use of copper-based products for CAN would contribute to the consumption of virgin or recycled material which are already overexploited resources from other industrial activities (Tabelin et al., 2021). The impact associated to some ICs resulted improved when compared to traditional PEN systems, in particular TCED, LU, FE, ME, TE, RU-f and RU-mm. On the other hand, the impacts associated to CC, OD, IR, Feco, and WU were lower in the PEN system compared to CAN100. This result is in contrast with the previous LCA study conducted on this topic (Ayer et al., 2016). Ayer et al. (2016) observed a reduction in all the impact categories considered in the copper alloy scenario with approx. 75 % of net recycling compared to traditional nylon cages. However, in the study of Ayer et al. (2016) the whole inputs (feed excluded) associated to Atlantic salmon farming in Chile were considered as well as another Life Cycle Impact Assessment method, thus limiting the comparison between the two studies. Notwithstanding this, only considering the sub processes associated to cage manufacturing, emissions, and disposal (i.e., net pen infrastructures. antifouling paint. metal leachate. and net-pen end-of-life see) some similarities between the two studies can be highlighted. The impact on metal depletion can be largely attributed to the AFP application, while emissions associated to AFP leaching determined the largest impact in marine ecotoxicity (Ayer et al., 2016). The lower impact of CAN cage in the study of Ayer et al. (2016) compared to the present one, could be explained by the higher consumption of AFP in the nylon cage system which was higher than 5 kg AFP kg^{-1} net.

In general, the environmental impact of PEN system is similar to CAN system when net is fully recycled at the end of the service life. However, AFP represents one of the main environmental hotspots in PEN systems. Moreover, the use of chemicals is often negatively associated with aquaculture by consumers (Ruiz-Chico et al., 2020). Therefore, a reduction in AFP consumption could contribute to increase social acceptability of aquaculture. In the current study, a single application of 1.17 kg AFP kg^{-1} net over the service life of the net was considered. However, the uptake of AFP could be higher. as those considered in (Ayer et al., 2016). By increasing the amount of AFP consumed by 20 % or using a different AFP product, the impact for some of the ICs considered could change, in particular, CC resulted slightly lower in the CAN system with 100 % of net recycled at the end of the service life then in the PEN system.

The present study focused only on the manufacturing and disposal of infrastructure, while all the other inputs traditionally associated with fish farming in mariculture cages were not considered. From comparative growth trials, an increased fish growth was observed when CAN was adopted instead of the traditional nylon or PE nets both in Atlantic salmon in Chile (Ayer et al., 2016) and Gilthead sea bream in the Mediterranean Sea (Yigit et al., 2018). In these trials, the higher growth rate was also associated with a reduced feed conversion rate (i.e., animal's efficiency in converting feed into increases of biomass) and thus a reduced consumption of feed, which is one of the main drivers of the environmental impact of aquaculture (Ayer et al., 2016; Yigit et al., 2018; Zoli et al., 2023a). Therefore. the adoption of CAN could lead to an "indirect" reduction of environmental impact associated with a reduced consumption of production inputs. in particular feeds.

In the present study the impacts associated to plastic emissions into water was not considered. In terms of environmental impact, plastic litter and emissions associated to plastic degradation are particularly relevant for aquatic biota and potentially for humans as micro- and nanoplastics could pass through seafood chains (Vázquez-Rowe, 2020). Consequently. the impact of plastic emissions has been included into LCA with the introduction of specific characterization factors for plastic emissions to be included in already existing impact categories such as Feco (Salieri et al., 2021) or new ones (Corella-Puertas et al., 2023; Maga et al., 2022). There are several potential contaminations ways of micro and nanoplastic in aquaculture which include also the fragmentation and degradation of larger plastic items (Ali et al., 2024). The most commonly detected microplastic were polypropylene. polyethylene.

polystyrene. and polyethylene terephthalate (Xie et al., 2024) which are among the main constituents of aquaculture infrastructures. However, so far plastic emissions were not included in LCA studies on aquaculture. Therefore, nor primary data, nor secondary data from literature were available for effectively consider plastic emissions in our study.

One of the limiting factors for the adoption of CAN technology in aquaculture is the high initial cost. which was approximately 39.69 $ m^{-2} for copper alloy mesh with a mesh of 2.4 cm compared to 16.87 $ m^{-2} for a 2 cm mesh nylon net coated with commercial AFP (Chambers et al., 2012). However. despite the initial cost difference. CAN cages could perform economically better than PEN in long-term use. decreasing operational costs such as net cleaning, repair, or replacement with new nets (Yigit et al., 2018). As previously highlighted, the adoption of CAN technology demonstrated a positive effect on fish growth and feed conversion rate which are particularly relevant in terms of economic profitability of fish farms. Moreover, it would be expected that the adoption of such technology on a large scale would lead to a more affordable price for aquaculture applications.

5. Strengths and limitations of the study

Aquaculture infrastructures were often neglected when addressing the environmental impact of aquaculture systems (Bohnes et al., 2019). In addition to nutrition, genetic improvement, and disease control, farm engineering aspects should also be considered with towards a better environmental and economic performance of a farm. To date, almost all marine aquaculture facilities use plastic nets although alternatives such as CAN are available. This study compares the repercussions in terms of environmental impact of the use of CAN nets instead of conventional PENs with a particular focus on the Mediterranean basin and the farming of European sea bass and Gilthead sea bream. However, no primary data were available from commercial-scale farms that use the CAN system in the Mediterranean. For this reason, primary data relating to small diameter cages (12 m) used for experimental purposes were upscaled to a larger size and commercial scale (30 m) using secondary data available in specialized literature and expert opinions. However, it was not possible to estimate some effects linked to the adoption of CAN systems, including: consumption of machinery and fuel for maintenance and consumption of feed and growth of animals in the two systems. Therefore, these sub-stages were excluded from the analysis. As well as the emissions and effects on ecosystems of the degradation of the plastic elements of infrastructure.

6. Conclusions

The use of CAN cages could contribute to extend the service life of marine aquaculture infrastructures compared to conventional PEN. However, the comparison of two rearing facilities is advantageous in terms of environmental impact only when a full recyclability of CAN is achieved, One of the main environmental hotspots of the PEN system, especially for HT-nc, RU-mm, AC, FE and Feco, is the use of AFP to prevent the formation of biofouling that contributes to reduce the service life of the cage. and increases the necessity of maintenance operations, and operational costs. Any increase in the use of AFP could lead to an increase in the impacts of PEN systems compared to CAN. However, the adoption of CAN technology is so far limited due to high initial costs. Therefore, a long-term economic assessment is required considering the effect of reducing other operational costs associated with the maintenance of PEN cages. Copper alloy net cages could represent an affordable and resilient solution for aquaculture, which could contribute to enhancing environmental, economic, and social performances of this industry, including a better consumer perception of aquaculture products following the reduction in the use of AFP. This study addressed the environmental impact assessment of marine aquaculture infrastructures by showing how traditional structures are sensitive to some key inputs, such as the use of AFP. The adoption of "alternative" systems such as CAN cages can represent a more sustainable solution, especially if the complete recyclability of the networks is achieved. This research can provide interesting insights to stakeholders on what interventions can be adopted in terms of infrastructure to improve the environmental performance of marine aquaculture. Further research is required to evaluate the performance of CAN system at a farm level. also considering possible implication in terms of maintenance and reduction of other inputs such as feed.

CRediT authorship contribution statement

Michele Zoli: Methodology, Data curation, Conceptualization. **Lorenzo Rossi:** Writing – original draft, Methodology, Data curation, Conceptualization. **Domitilla Pulcini:** Writing – original draft, Data curation. **Jacopo Bacenetti:** Writing – review & editing, Writing – original draft. **Fabrizio Capoccioni:** Writing – original draft, Data curation. **Arianna Martini:** Writing – original draft, Investigation, Conceptualization.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquaeng.2024.102462.

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