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Life Cycle Assessment (LCA) Proves that Manila Clam Farming (*Ruditapes Philippinarum*) is a Fully Sustainable Aquaculture Practice and a Carbon Sink

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Abstract: Manila clam (*Ruditapes philippinarum*, Adams and Reeve, 1850) farming is a quantitatively important and valuable form of aquaculture production worldwide but, to our best knowledge, no life cycle assessments (LCA) have been undertaken on it. However, being a filter feeder and producing a thick shell during the growing cycle, the capacity of Manila clam to remove nutrients, carbon, nitrogen and phosphorous from the marine environment potentially has some positive effects on the environment. This study was performed in the Sacca di Goro lagoon, located in the southernmost part of the Po River Delta, in the northwestern Adriatic Sea. The LCA of clam farming from a cradle-to-gate perspective have been carried out, including the production stages as seed procuring, sowing, harvesting, depuration and packaging to obtain 1 ton of fresh ready-to-sell clams. The results show that area preparation, fuel combustion and plastic bags were the main contributors to the environmental impacts. The potential capability as a carbon sink of 1 ton of clams has been calculated and the effects on eutrophication reduction by fixing nitrogen and phosphorous in shells, with a net sequestration of 444.55 kg of CO_2, 1.54 kg of N and 0.31 kg of P per year.

Keywords: Manila clam; *Ruditapes philippinarum*; aquaculture; life cycle assessment (LCA); sustainability; environmental impact; carbon sink

1. Introduction

As the global population continues to grow, the demand for and production of food, especially seafood from aquaculture, will continue to be an essential element in the future of our food security and fill the shortfall that exists between the global demand for seafood products and the available supply from wild-stock fisheries [1]. In fact, aquaculture, now 50% of the total fishery harvest, is one of the fastest growing sectors in the food industry, and its production is expected to at least double by the mid-twenty-first-century. It has a growing international relevance to achieving the United Nations' Sustainable Development Goals, while capture fisheries remain flat. The continuously expanding sector of marine aquaculture, for example, has tremendous potential to help feed the growing human population sustainably (for example, Sustainable Development Goals 2 and 14) [2]. In this regards, the marine aquaculture of bivalve shellfish (clams, scallops, mussels, oysters, etc.) is a particularly attractive form of aquaculture because it can become the ultimate sustainable and green industry [3]. In fact, unlike other forms of aquaculture, or agriculture for that matter, this type of farming does not require the addition of artificial food, supplements or medicines, because they feed entirely on particulates naturally present in the water column [4]. Moreover, besides their provisioning potential, bivalves provide regulating ecosystem services in coastal waters, such as the mitigation of eutrophication, carbon sequestration, coastal defense, the recirculation of anthropogenic waste from land or coastal activities and indirect benefits arising from shellfish beds and reefs [5,6].

Sustainability is a key issue for further expanding the bivalve sector, which requires a comprehensive assessment of the environmental, economic and social impacts of the production system [7,8]. Environmentally sustainable production is needed to ensure that the impacts of food production do not compromise other ecosystem services and do not impact on the environment at a local or global level [9]. Socially and economically sustainable production is needed to ensure that the communities, industries and supply chains that generate food continue to function and provide socially and ethically acceptable working conditions for the people involved [10].

Life cycle assessment (LCA) is a widely accepted methodology to provide metrics for assessing the environmental performances of products and processes [11]. LCAs applied to food systems and agricultural production date at least from the mid-1990s [12,13], but has been applied to fisheries and aquaculture research only in the last decade [14]. There are already several examples in the literature concerning the application of LCAs to non-fed aquaculture products, and in particular bivalves. Iribarren et al. has long been working on LCA applied to mussel [15,16] and oyster [17] farming, as have Aubin et al. [18], Lourguioui et al. [19] and Tamburini et al. [20,21].

However, to our best knowledge, there is no literature on the LCA of clams, even though this is one of the most appreciated and commercially exploited bivalve mollusks in the world [22]. In this context, the aim of this study is to fill this gap and use LCA as a tool for assessing the environmental impact of Manila clam culture in one of the oldest and most important area in Italy, the Sacca di Goro, located in the northern Adriatic Sea. Overall, clam farming has been analyzed for its environmental impact, which in turn can have local socio-economic implications.

Manila clam (*Ruditapes philippinarum*) (Adams and Reeve, 1850) is by far the most commonly cultured clam species, with a total catch of 4,229,000 tons per year, which represents about 25% of global mollusk production in 2018 [23].

The natural population of the Manila clam is distributed over the western coasts of the Pacific Ocean, ranging from the Philippines to Russia [24]. The majority of the world clam production comes from this area, with China the largest worldwide producer (about 94%) [25]. As a species of commercial value, Manila clam has been introduced to several part of the world to become permanently established in several countries [26]. The species was accidentally introduced to the Californian coasts during the 1930s along Pacific oyster *Crassotrea gigas* seed import from Japan, and then spread along the entire Pacific coastline up to Alaska [27]. Overfishing and irregular catches of the native (European) *Ruditapes decussatus* led to the import of *R. philippinarum* into European waters. In particular, clams were firstly introduced in France to cope with production problems with the native clam species in the early 1970s, and later they were further introduced in the UK, Spain and Norway [28]. In Italy, the Manila clam was introduced from 1983 on the northern Adriatic coast, and immediately after its introduction it naturalized in many favorable transitional environments, such as the lagoon of Venice, Goro, Marano and Grado [29]. Due to its higher growth rate and better tolerance to temperature and salinity variations, and to eutrophication, Manila clam took the niche already left free by the native species *R. decussatus*, too sensitive to eutrophication, and rapidly became one the most important economic activities within national aquaculture [30]. Now, Manila clam rearing, with an annual production of about 55.000 tons, makes Italy the leading producer in Europe and the second worldwide [31]. From a regional point of view, this activity leads to a key economic sector that in terms of quantity accounts for more than 90% of European clam production [23]. Beyond the local and national relevance of this comprehensive case study, the results of LCA analysis are interesting within a global scenario of policy and decision making because they address sustainability, making Manila clam farming comparable with other much less sustainable forms of aquaculture production.

We also investigated the clams' farming potential capability as a carbon sink by their net carbon stocking through calcification and the effects on eutrophication reduction by fixing nitrogen and phosphorous in shells.

2. Materials and Methods

2.1. Study Area

This study was performed in the Sacca di Goro lagoon, a basin located in the northern Adriatic Sea, in particular in the southernmost part of the Po River Delta (Figure 1). The lagoon covers an area of approximately 27 km^2 and is shallow (mean water depth, 1 m) and brackish, and it has been exploited since 1985 for *R. philippinarum* farming. The lagoon is separated from the Adriatic Sea by a narrow sandy barrier with two mouths of about 0.9 km each regulating saltwater exchanges, and it has four freshwater inlets. At present, approximately one-third of the total lagoon surface are devoted to clam farming, especially in the central part of the lagoon in front of the main connection with the open sea, where the water exchange rate is higher and the sediments are sandier. Clam seeds are collected under a strict set of rules in natural nursery areas and then seeded in licensed areas at densities generally maintained at around 1000 adult individuals per square meter [32]. Farming principally consists of collecting seed from natural areas and redistributing it in licensed growing areas. Seed can be produced from hatcheries, but actually in small quantities and only when natural seed are less available. Manila clams seed (5–10 mm in shell length) are continuously collected in the lagoon mouth or outside the lagoon, along the sand banks, and immediately sown in the licensed areas until the commercial size, in the range 3–4 cm, is reached. In the Sacca di Goro, due to high primary productivity and the natural availability of a reach and variable phytoplanktonic *pabulum*, this occurs in the very short time of 8–10 months. Overall product losses from sowing to harvest amount to about 30%.

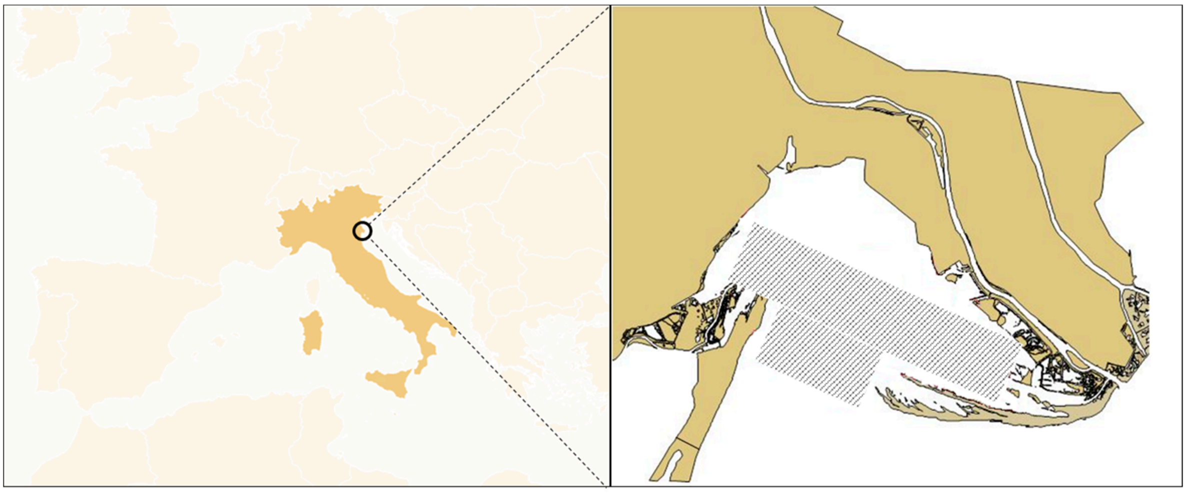

Figure 1. Manila clam farming areas in the Sacca di Goro lagoon, Adriatic Sea coastline, northeast of Italy (44.78–44.83° N and 12.25–12.33° E). The shadowed areas approximately represent the portion of the lagoon licensed for clam nursery and farming.

It has also become a common practice to move large number of clams from the lagoon to more open areas, directly outside the lagoon mouth, and vice versa, to avoid the loss of product due to eutrophication and summer anoxia [33]. Despite its small dimensions, the Sacca di Goro lagoon supports the local economy and provides the main revenue of the resident population, which is about €60–70 million per year. Shellfish farming is socially relevant: it ensures about 1600 direct job positions, corresponding to about 60% of active population (aged 14–65), plus employment in seafood industries, commercial and side activities, e.g., shipbuilding [34].

Clam farming is managed by cooperatives of fishermen that access licensed areas, under the control of regional and local authorities [35]. Usually the overall licensed areas and inner sub-areas are visually delimited by wood poles (Figure 2). Sub-areas have an average extension of 2500 m^2. In the portion of lagoon covered by this study, 3000 inner poles and 250 outer poles were necessary to delimitate the licensed areas. The product quantity, which is delivered daily to the market, is controlled by the cooperative consortia in order to guarantee both food quality and adequate revenue.

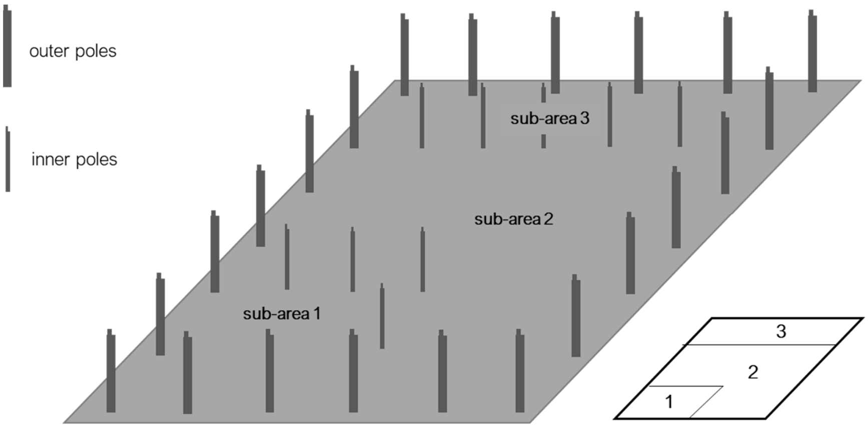

Figure 2. Example of clam farming licensed area and sub-areas delimitations.

2.2. LCA Goal and Scope, System Boundaries and Functional Unit

An LCA was carried out to calculate the environmental impacts of Manila clams farmed in the Sacca di Goro lagoon, according to the Protected Geographical Indication (PGI) label. The functional unit was 1 kg of fresh clams (with shell), which is the principal way fresh clams are distributed to the market from Goro. The system boundaries, from seed procuring in the nursery areas to packaging, include all on-growing stages, equipment, technical clothing, materials, electricity, fuel and water uses, as well as the construction of capital goods (i.e., boats for farming, concrete tanks for depuration) (Figure 3). Emissions to air and sea and waste have been also included in the analysis. A cradle-to-gate analysis was undertaken. The distribution, purchasing and consumption phases have been excluded from the boundaries because of the lack of reliable data.

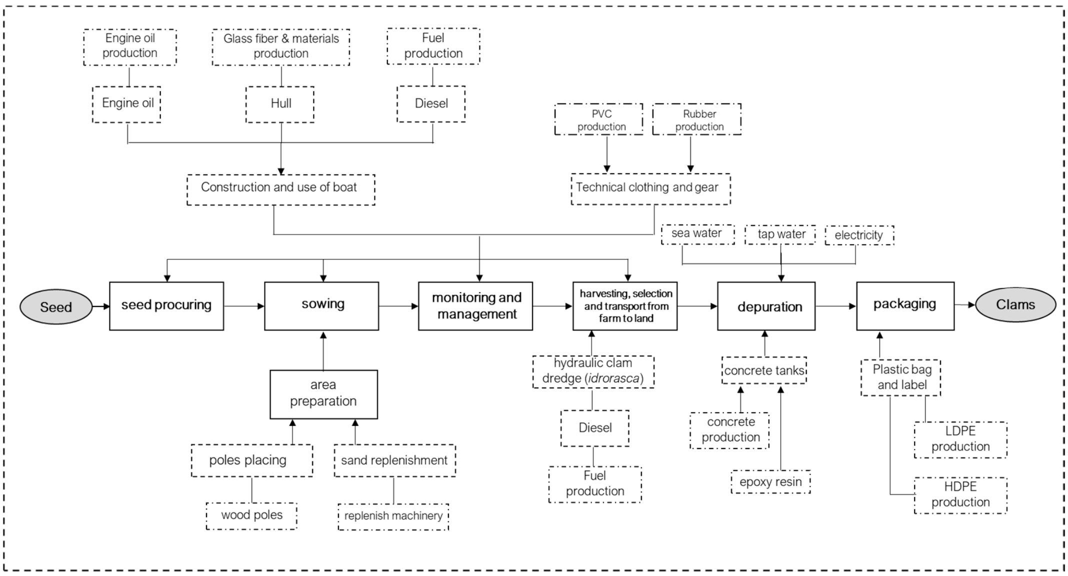

Figure 3. The system boundaries considered in this life cycle assessment (LCA) study. Foreground processes are depicted by solid boxes; background process by dashed boxes; raw materials, electricity, fuels and water production processes by dash-dotted boxes; mass flows by solid arrows; and products by grey circles. (PVC = polyvinylchloride; HDPE = high density polyethylene; LDPE = low density polyethylene).

2.3. Life Cycle Inventory (LCI)

Primary data for clam farming were estimated based on interviews with 119 shellfish farmers operating in Sacca di Goro lagoon, collected in winter 2020. They harvest a total of 988 tons of clams per year.

The only impact for clam seed was related to seed procuring because it grows spontaneously in the seabed without the need of any external input for growing and can be considered as an input without impact.

Area preparation involves two operations: yearly sand replenishment to improve the quality of sandy seabed; and placing the inner (length, 3–5 m; diameter, 7–8 cm) and outer (length, 9 m; diameter, 20–30 cm) chestnut wood poles, which have to be replaced every 3 and 5 years, respectively. The sowing operation does not have any input contribution because usually it is executed by the manual spreading of seeds by farmers. During the growing period, the area has to be monitored daily in order to handle supplementing or thinning out clams and optimizing the shellfish yield. Monitoring and management operations, as well as seed procuring, sowing and harvesting, have been carried out using a 7.5 m fiberglass boat. In the current farming conditions, a boat serves 2.43 farmers, with a productive capacity of about 20 tons/boat per year. The total number of boat trips per growing season is 10 for sowing and 200 for monitoring, management and harvesting (average distance travelled per trip, 4 nautical miles). The lifespan of a boat has been estimated at 35 years. Gasoline is used as fuel, engine oil as lubricant (Table 1). All input suppliers are located in Goro, with a negligible contribution of transport. The analysis does not include the transports of raw materials to suppliers.

Table 1. Life cycle inventory (LCI) of clam farming in the Sacca di Goro lagoon. All inputs are referred to 1 kg of fresh clams harvested and packaged with shell. (PM = particulate matters).

Input	
From the Technosphere	
Materials and Fuels	
Low-density polyethylene (LDPE) (g)	6.0
Polyvinyl chloride (PVC) (g)	0.8
Rubber (g)	<0.1
Concrete (kg)	22.5
Chestnut wood (m^3)	0.3
Gasoline (g)	30
Engine oil (l)	0.2
Electricity (kW)	2.3
Emissions to air	
Carbon dioxide (kg)	8.28
Nitrous oxide (kg)	0.13
Sulfur oxide (kg)	0.22
Methane (kg)	0.21
Non-methane volatile organic carbon (NMVOC) (kg)	0.13
Chemical oxygen demand (COD) (kg)	0.10
Dissolved organic carbon (DOC) (g)	3.50
Heat, waste (J)	4.21
PM < 2.5 µm (g)	3.4
PM > 2.5 µm and < 10 µm (g)	27.0
PM > 10 µm (g)	38.0
From the Environment	
Resources	
Seawater (m^3)	2.28
Freshwater (m^3)	0.3

Clams are harvested throughout the year, with an intensification during higher-demand periods. Harvesting has been carried out by means of a boat-engine driven hydraulic dredge (called an idrorasca). The first clam selection is done on-board, with broken empty shells simply thrown back into the sea. Then, clams are transported to the land and held in aerated depuration tanks for at least 24–48 h. The purification station, shared at 20% with mussels, consists of 18 tanks with a 520 m^3 overall capacity made of concrete with a waterproof epoxy-resin coating. Water from the lagoon is pumped into the tanks for replacing 20% of their capacity per day. In addition, 5043 m^3/year of freshwater is consumed for shellfish washing. Finally, clams are packaged in 1 kg low-density polyethylene (LDPE) bags for sale. All background data, such as fuel, engine oil, hull, replenish machinery and wood poles production, were taken as dummy processes from Ecoinvent™ v.3.6 database [36]. Electricity consumption is due to water pumps in depuration. The actual Italian electric energy mix, containing about 38% of renewable energy [37] has been used. Technical cloths include diving vests in Polyvinyl chloride (PVC), rubber gloves and rubber boots, with a lifespan of 3 months to 2 years. Plastic materials recovery and recycling have been included in the analysis, except for the LDPE bag packaging, for which the end-of-life is managed out of the system boundaries.

2.4. Elemental Balance (Carbon, Nitrogen and Phosphorous)

Fresh Manila clams cultivated in the Sacca di Goro are formed of 10% flesh and 90% shell that in turn is made up of calcium carbonate at 96% [38]. They have a dry matter content of about 55%. The amounts of C, N and P fixed in dry clam shells have been estimated using data from Zan et al. [39], who investigated the dynamics of content of biogenic elements of *T. philippinarum*. The average element contents of a dry shell were 9.82 ± 0.38 mol/kg, 0.11 ± 0.02 mol/kg, 0.01 ± 0.00 mol/kg for C, N and P, respectively. As is well-known, the clam shells grow through biogenic calcification, using calcium cation (Ca^{++}) and carbon dioxide in the form of dissolved bicarbonate (HCO_3^-) to precipitate calcium carbonate ($CaCO_3$) [40]:

$$Ca^{++} + 2HCO_3^- <-> CaCO_3 + CO_2 + H_2O \quad (1)$$

During biogenic calcification, CO_2 is not only sequestered by shells but also released, following the fate of being emitted into the atmosphere or lowering the carbon-sink capacity of the sea, preventing further carbon dioxide capture from air [41]. Carbon dioxide released from calcification has been estimated by applying the formula proposed by Ray et al. [42] to clams farmed in the Sacca di Goro lagoon:

$$CO_2\mathit{released} = (\mathit{Clams\ shell\ mass\ at\ harvest}) \times \Psi \times (\%CaCO_3\ \mathit{in\ clam\ shell}) \times 0.44 \quad (2)$$

where 0.44 is the ratio of the relative molecular masses of CO_2 and $CaCO_3$ (44.01 and 100.08, respectively) and Ψ as the ratio of the released CO_2 and precipitated carbonate [43]. Ψ can be calculated as a function of the pH, temperature, salinity, and pCO_2 of the growing site and has been averagely estimated to be 0.6 in seawater [44].

The estimated content of C, N and P the shell per ton of clams harvested and discarded, and CO_2 released by calcification are reported in Table 2.

Table 2. C, N and P fixed in shell and CO_2 released by calcification for 1 ton of clams harvested.

	Clams Harvested
C fixed in shells (kg)	88.00 ± 3.34
N fixed in shells (kg)	1.54 ± 0.14
P fixed in shells (kg)	0.31 ± 0.02
CO_2 released by calcification (kg)	124.20 ± 6.21

2.5. Life Cycle Impact Assessment (LCIA)

The ReCiPe Midpoint (H) (PRé Consultants, Amersfoort, the Netherlands) method [45] and the open-source package OpenLCA^{TM} v.1.8 (GreenDelta, Berlin, Germany) were used for the impact assessment and the overall LCA modeling, respectively. Emissions to air were calculated directly by the software, based on input data and mainly derived from diesel combustion. The impact categories were: eutrophication potential (EP), climate change as global warming potential (GWP), photochemical oxidant formation potential (POFP), ozone layer depletion potential (ODP), acidification potential (AP), fossil depletion (FD), water depletion (WD), human toxicity potential (HTP) and marine aquatic eco toxicity potential (MAETP). In this study, allocation was not necessary because clams were the sole product.

The environmental impacts of clam farming have been calculated from aggregated and averaged data collected by interviews. A Monte Carlo analysis with 1000 runs was carried out with OpenLCA^{TM} v.1.8. From the Monte Carlo simulation, all impact categories showed a right-skewed asymmetrical distribution. Uncertainty of the result of each impact category was expressed as a 95% confidence interval of the distribution.

3. Results and Discussion

The results of LCA, expressed per 1 ton of harvested clams, are summarized in Table 3, whereas Figure 4 shows the contribution of inputs and production phases to each impact category.

Table 3. Average impacts from LCA of 1 ton of clams harvested in the Sacca di Goro lagoon. CV% are based on Monte Carlo simulation uncertainties.

Impact Category	Value	CV%	Unit
Climate change—GWP100 *	75.95	26%	kg CO_2 eq.
Acidification potential (AP)	0.56	34%	kg SO_2 eq.
Eutrophication potential (EP)	0.16	24%	kg PO_4 eq.
Fossil depletion (FD)	60.29	18%	kg oil eq.
Water depletion (WD)	69.96	32%	m^3
Ozone layer depletion potential (ODP)	1.81×10^{-5}	33%	kg CFC-11 eq.
Photochemical oxidant formation potential (POFP)	0.75	33%	kg NMVOC eq.
Human toxicity potential (HTP)	8.63	60%	kg 1,4-DCB eq.**
Marine water aquatic ecotoxicity potential (MAETP)	1.89	46%	kg 1,4-DCB eq.

* GWP100, global warming potential for 100 year-time horizon; ** 1,4-DCB, 1,4 dinitrobenzene equivalent (eq.).

The amount of carbon dioxide emitted in clam farming, mainly a burden on climate change, is estimated as global warming potential for a 100 year horizon [46]. The EP category is affected by nitrogen emission to fresh and marine water, while AP, ODP and POFP are influenced by emissions to air. In particular, nitrous oxides contribute to POFP, together with volatile organic compounds (NMVOC), both acting as precursors of ground-level ozone layer. As it is well known, ozone at ground level is a harmful air pollutant, being the main ingredient in smog, because of its effects on people and the environment [47]. AP is due to sulfur dioxide emissions, which assessed the potential occurrence of atmospheric acidification. HTP and MAETP principally reflect the effect of heavy metals traces (i.e., cadmium, nickel, chromium, arsenic, mercury) on human health or ecosystems. The heavy metals are emitted mainly as a result of various combustion processes and from industrial activities. As well as polluting the air, provoking health damages by direct exposure, heavy metals can be deposited on terrestrial or water surfaces and subsequently build up in soils and sediments, and can bio-accumulate in food chains [48], becoming indirectly highly toxic to terrestrial and aquatic organisms, as well as to humans.

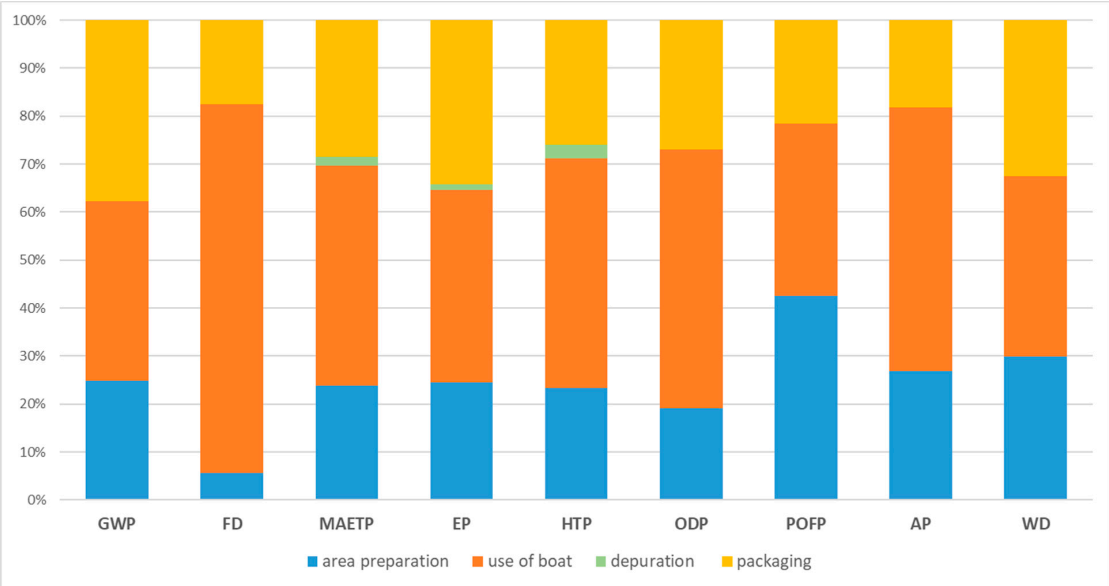

Figure 4. Contribution to environmental impacts of inputs and production phases for farming 1 ton of clams.

The main contributors to all impact categories as production stages are area preparation and packaging, whereas the main contributor as an input is the boat and the related diesel use. The most impactful operations in the area preparation are the excavation by hydraulic digger for sand replenishment and the preservative waterproof treatment on the chestnut wood poles. On the other hand, HDPE production as granulate and film extrusion for plastic bags is an overburden on packaging stages. The use of the boat refers to diesel combustion and engine oil used during the growing season to support the boat trips. As expected, it shows the larger effect on fossil resource depletion. The pump station in the clam purification building slightly influences MAETP, EP and HTP.

At this stage, clam farming appears to be more sustainable than mussel or oyster farming due to the fact that some farming operations are still carried out manually by farmers and no artificial plant is needed for cultivation. For the sake of comparison, for mussel and oyster aquaculture on long-line plant a GWP of 137 kgCO_2 eq./ton [20] and 1850 kgCO_2 eq./ton [21], respectively, has been previously calculated for the same area. Comparing the environmental impacts of different products is always a contestable affair, but it emphasizes the effective sustainability of clam farming, principally based on the fact of the use of the seabed for shell growing. Another interesting point is the reduced use of plastic materials, which is almost limited to technical clothing and packaging. The former has a negligible environmental impact, because all cloths are properly recycled; the latter is used and managed exclusively out of the sea, so cannot directly contribute to microplastics pollution except from through poor behaviors by end-consumers, which are impacts out of the system boundaries of this study.

Comparisons with other shellfish farming systems, such as those reported in Iribarren et al. [15–17], Aubin et al. [18] and Lourguioui et al. [19], make less sense, because they applied LCA to other production systems and in other geographic areas. It is worthwhile to note that, as mentioned above, this study represents the first attempt to apply LCA to clam farming.

In order to investigate possible improvement with respect to environmental performance in clam farming, our results support the statement that clam farming is the most sustainable among the other studied mollusks, emerging the intrinsic value of this aquaculture practice. The LCA has been demonstrated to be a suitable method of analysis to perform the environmental characterization of the entire supply chain, emphasizing the fact that the final product is obtained without using feed or pesticides but only exploiting the lagoon natural resources. This aspect deserves particular mention, because, different from other forms of aquaculture, or agriculture for that matter, none of the food consumed by clams is added to the environment. They feed entirely on naturally occurring particulates in the water column. The minimization of the negative effects, both direct and indirect, of aquaculture farming is considered to be a fundamental issue of management plans in heavily exploited ecosystems such as Sacca di Goro and prove to be necessary as a basis for sustaining future environmental labeling and local products protections.

The actual constraint is to encourage a cultural and social revolution within the Sacca di Goro community in order to progressively promote forms of sustainable aquaculture, and thus convey to consumers a new perception of the clam farming eco-friendly business, because it can be compared in all respects to a renewable resource.

Clam Aquaculture as Net Carbon Sink

Nutrient elements are stored in the shell of shellfish through $CaCO_3$ precipitation and they can be removed from marine ecosystem when clams are harvested [49,50].

It is widely recognized that only a minor fraction of elements, such as carbon, nitrogen and phosphorus are exported with harvested clam at the end of farming cycle [51,52], but the ecological effects of biogenic elements removal through clam harvest and shell deposition on ecosystems deserve particular attention in the overall elemental balance, especially toward the fate of carbon.

For the sake of clarity, it is worthwhile to note that carbon storage in clam flesh has been excluded from the analysis, since it is considered part of the short C cycle [53], and thus quickly reemitted in environment by clam metabolism or clams' death. CO_2 from clams' respiration has not been included because it is assumed to be reused in the photosynthesis processes and to enter in biological cycles without given an effective contribution to net emissions [18].

As indicated by the stoichiometric equilibrium of Equation (2), during biogenic calcification, part of the carbon dioxide from the environment (in form of hydrated HCO_3^-) is precipitated in shells and partly released back as a reaction product. Moreover, part of that released carbon dioxide turns back to anion HCO_3^-, while the rest remains as CO_2 (the amount of CO_2 that remains as CO_2 and does not form the hydrated anion is indicated as Ψ). Due to these two opposite consequences, a debate has developed as to whether shellfish can be considered as a net carbon dioxide source or sink. As argued by Filgueira et al. [54], we followed an ecosystem-based approach whereby the amount of CO_2 released during respiration would have not to be counted, since consumers—such as bivalves—are considered to be simply recycling CO_2 only temporary sequestered by phytoplankton. Their activity just makes a cycle faster, from the uptake to the organication into phytoplankton biomass, to cell senescence and release to the water as CO_2, which is anyway short, in the order of days or a few weeks. Conversely, CO_2 sequestration in Manila clam shells may be considered permanent, and thus a positive part of long-term C trading system.

Based on the data reported in Table 2, we estimated the annual removal of carbon, nitrogen and phosphorous, precipitated in shell via clam harvest, in 1100.0, 20.9 tons and 4.1 tons per year, respectively.

Bartoli et al. [51] found that in Sacca di Goro, the anthropogenic removal amounts of nitrogen and phosphorus were 46 tons and 10 tons, respectively, which accounted for 5% and 25% of the annual nitrogen and phosphorous loads entering the lagoon from freshwater inputs. Nizzoli et al. [32] showed that the removal amounts of nitrogen and phosphorus through clam harvest were 16 tons and 0.9 tons, respectively, when the clam annual yield was 6000 tons. Compared with the previously studies, these quantities were larger in this study. The removal of biogenic element contents by the harvest and natural death of Manila clams would help to control the biomass of phytoplankton, with an indirect effect on eutrophication, which still needs to be further studied due to its possible feedback due to nutrient regeneration. Undoubtedly, the available data show that Manila clam has a central role in the ecological regulation of the lagoon metabolism.

In terms of carbon dioxide balance, based on Equation (2), 88.00 kg of carbon bio-calcificated as $CaCO_3$ per ton of clams corresponds to 644.70 kg CO_2 captured from the surrounding environment, whereas the amount of CO_2 released has been calculated as 124.20 kg. Even including the amount of CO_2 emitted for clam farming operations in the balance, quantified as 75.95 kg by the LCA (see Table 3), the net balance is negative, with a net sequestration of 444.55 kg of CO_2 per ton of clams. In other words, 1 ton of clams at the end of their growing cycle can act as a net sink for 54.50 kg of C, which corresponds yearly to a total of 723.8 ton of C in the whole lagoon.

The net carbon sequestration underlines, in an incontrovertible way, the sustainability of venericulture, and in a more general sense, of the rearing of filtering bivalves. On the basis of the LCA analysis of the entire production cycle, Manila clam rearing is configured as fully sustainable with respect to carbon dioxide emissions. The LCA analysis has also reinforced the potential mitigation action against eutrophication, evidenced by nitrogen and phosphorus budgeting at the scale of the whole lagoon, although this term needs to be further deepened.

An effective comprehension of the connections between the natural environment and anthropic activities is fundamental for assuring sustainable development in all fields, including mollusk aquaculture. By means of an LCA, this study shows that clam farming has lower environmental impacts in comparison with other shellfish production due to the absence of constructed plants for cultivation and the reduced uses of plastic materials. Moreover, the results have demonstrated the positive effects on the overall carbon balance, proving that clam aquaculture could play a significant role as a carbon sink. At the local scale, these findings can help to support the enhancement and diffusion of the sector from an economical and societal point of view, but also improve the coastal ecosystem quality. The main role of clam aquaculture is food provision, but we have demonstrated that they also provide environmental services through carbon dioxide capture, and therefore contribute to improving the capacity of coastal ecosystem to become a net sink for carbon of anthropic origin. Clam aquaculture can thus also be considered in the wider perspective of climate change mitigation.

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