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Article

Life Cycle Assessment of Carbon Cycling and Environmental Impacts in Mussel Farming

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Abstract: Under China's dual carbon targets and the green transition of aquaculture, understanding carbon flows and life cycle environmental impacts is important for evaluating the ecological performance of mussel farming. This study assessed typical mussel aquaculture areas in Zhejiang Province using life cycle assessment combined with carbon flow analysis, covering seed stocking, grow out and harvesting stages. The carbon flow analysis used 1.45 kg C as the normalized total carbon use basis. Of this amount, 0.21025 kg C was allocated to carbon removal, 0.97585 kg C to storage related pathways, 0.09860 kg C to respiration related release, and 0.16530 kg C to calcification related release. Carbon removal and storage related pathways together accounted for 81.8% of the normalized carbon use basis, indicating that the model allocated a larger proportion of carbon to potential removal and local retention pathways than to release pathways. This allocation pattern is consistent with a potential weak and seasonally constrained carbon sink function under favorable environmental conditions, although it does not independently demonstrate net atmospheric CO_2 removal. The main environmental impact categories were terrestrial ecotoxicity potential (TETP), which contributed 35.03%, human non-carcinogenic toxicity potential (HTPnc), which contributed 22.79%, human carcinogenic toxicity potential (HTPc), which contributed 18.30%, terrestrial acidification potential (TAP), which contributed 8.51%, fossil resource scarcity potential (FFP), which contributed 5.65%, and freshwater ecotoxicity potential (FETP), which contributed 4.89%. For monetized environmental impacts, HTPnc made the largest contribution, followed by FFP, TAP, global warming potential (GWP) and fine particulate matter formation potential (PMFP). Overall, mussel aquaculture may contribute to local carbon cycle regulation and may provide a weak, seasonal and context dependent carbon sink function; however, the present results do not independently demonstrate that the farming system functions as a net atmospheric CO_2 sink.

Keywords: mussel aquaculture; life cycle assessment; carbon cycling

1. Introduction

Global climate change, resource pressure and the green transition of aquaculture have drawn increasing attention to the carbon cycling functions and environmental impacts of aquatic food production systems 12. Aquaculture has become an important component of global food supply, but its environmental performance varies greatly among species, production modes and management practices. Compared with feed dependent aquaculture, shellfish farming is often regarded as a relatively resource efficient production system because shellfish can obtain food directly from natural seston and suspended organic particles in the water column 34. This biological feature gives shellfish aquaculture both production value and ecological significance. As typical filter feeding organisms, shellfish remove particulate organic matter, regulate nutrient transfer, and retain part of the carbon associated with filter feeding and calcification in shells and soft tissues 34. Through filtration, biodeposition, metabolism and excretion, mussels also modify the transformation of organic and inorganic carbon in aquaculture waters, thereby participating in local carbon cycling and water quality regulation 56.

Mussel aquaculture is an important type of shellfish farming in China and has ecological functions that differ from those of many fed aquaculture systems. During growth, mussels usually require little or no artificial feed, and their biomass accumulation mainly depends on phytoplankton, organic detritus and suspended particles in the surrounding water. This reduces the direct demand for feed inputs and can help lower some upstream environmental burdens. At the same time, mussels can improve water clarity through filter feeding and transfer suspended particulate matter into biodeposits, which may affect sedimentation, nutrient regeneration and benthic processes 35. These characteristics make mussel aquaculture relevant to discussions on ecological aquaculture, nutrient removal and carbon management. However, mussel farming should not be evaluated solely on the basis of biological carbon retention. Its production chain still includes facility operation, water pump aeration, water heating, routine inspection and management, harvesting, transportation, cleaning, sorting and packaging. These activities consume electricity, fuel, materials and labor, and may generate environmental burdens through energy use, pollutant emissions and resource consumption 7.

The environmental performance of mussel aquaculture therefore needs to be evaluated from a whole system perspective. A narrow assessment based only on carbon stored in shells or soft tissues may overestimate ecological benefits or overlook important environmental costs. Carbon retained in biomass is only one part of the system. Carbon can also be released through respiration, metabolism and excretion, transformed among dissolved and particulate pools, or transferred to sediments through biodeposition. In addition, the environmental burdens arising from aeration, heating, harvesting and post harvest treatment may offset part of the ecological benefits associated with filter feeding and carbon storage. For this reason, a combined assessment of carbon flow processes and life cycle environmental impacts is needed to provide a more balanced understanding of mussel aquaculture.

Life cycle assessment (LCA) provides a standardized methodological framework for quantifying resource consumption and environmental burdens across the full production process 89. It can define system boundaries, compile input and output inventories, and compare the contribution of different stages to environmental impact categories. In aquaculture research, LCA has been widely used to assess impacts such as global warming, acidification, eutrophication, ecotoxicity, resource use and energy demand 710. For mussel aquaculture, LCA is particularly useful because it can connect farming operations with environmental burdens that are not always visible from biological assessment alone. For example, even when mussels do not require artificial feed, energy use during water pumping, aeration, transport and processing may still contribute to global warming potential, fossil resource scarcity, particulate matter formation and toxicity related impacts. LCA can therefore help identify which production processes should be prioritized for environmental optimization.

Current studies on shellfish aquaculture have provided valuable knowledge on filtration, nutrient removal, biodeposition, shell carbonate formation and biomass carbon storage 3,6. Many studies have considered shellfish as a potential contributor to blue carbon or coastal carbon management because carbon can be stored in shells and tissues. However, carbon accounting in shellfish aquaculture remains complex. Shell formation, soft tissue growth, respiration, metabolic release and interactions with water chemistry all influence the net carbon balance. Recent studies have presented contrasting interpretations of the role of bivalve farming in coastal carbon budgets. From an ecosystem scale perspective, interactions among microalgae, mussels and microorganisms may promote phytoplankton turnover, the downward transfer of particulate organic carbon and the microbial transformation of bioavailable carbon into relatively persistent forms. This perspective suggests that mussel farming may have a potential carbon sink function under favorable environmental conditions [11].

In contrast, carbon retained in shells, soft tissues or biodeposits cannot automatically be interpreted as atmospheric CO_2 sequestration. Shell calcification may release CO_2 and alter the relationship between dissolved inorganic carbon and total alkalinity, while respiration and organic matter remineralization may return carbon to the water column [12]. Therefore, whether mussel farming functions as a net CO_2 source or sink depends on the combined effects of primary production, respiration, calcification, biodeposition, microbial transformation, sediment burial and air–water CO_2 exchange. Accordingly, the present study treats a weak and context dependent carbon sink function as a hypothesis to be evaluated through carbon allocation analysis rather than as directly verified net atmospheric CO_2 removal. Moreover, previous studies have often paid more attention to shell carbon and soft tissue carbon, while less attention has been given to the transformation of different aquatic carbon pools, including dissolved inorganic carbon (DIC), particulate organic carbon (POC), dissolved organic carbon (DOC), refractory dissolved organic carbon (RDOC) and labile dissolved organic carbon (LDOC) [13,14].

Among these carbon forms, DOC is an important component because it contains organic carbon fractions with different biological availability and turnover characteristics. LDOC is relatively bioavailable and can be rapidly utilized or remineralized by microorganisms, whereas RDOC is more resistant to microbial degradation and may remain in aquatic environments for longer periods [14,14]. However, RDOC represents relative persistence rather than permanent carbon sequestration.

In mussel farming systems, POC is ingested through filter feeding and contributes to soft tissue production, respiration, excretion and biodeposition, whereas DIC is involved primarily in carbonate system processes associated with shell calcification. Mussel metabolism, excretion and the dissolution or degradation of organic particles may contribute to the DOC pool. This pool can be conceptually represented as containing LDOC and RDOC fractions, but the proportions and persistence of these fractions depend on microbial activity, water exchange and local environmental conditions. Accordingly, DOC, LDOC and RDOC were retained in the present study as conceptual carbon transformation pathways rather than as independently quantified sequestration pools. These pathways may contribute to local carbon retention and are relevant to the potential weak carbon sink function of mussel farming, but they cannot by themselves demonstrate permanent carbon storage or net atmospheric CO_2 removal. Combining this carbon flow perspective with LCA makes it possible to evaluate potential ecological functions together with the environmental burdens generated by energy and material inputs.

Therefore, there is a need to build an analytical framework that connects carbon flow analysis with LCA. Such a framework can clarify how carbon enters, transforms and leaves the mussel aquaculture system, while also identifying the production processes responsible for major environmental impacts. This integrated approach is especially useful for evaluating whether mussel aquaculture can provide potential local carbon retention benefits while maintaining a relatively low life cycle environmental burden. It also provides a basis for targeted management, such as reducing electricity consumption in aeration, optimizing harvesting and transportation, improving post harvest processing, and controlling facility related inputs.

This study focuses on typical mussel aquaculture areas in Zhejiang Province, China. Zhejiang has diverse aquaculture waters and representative mussel farming practices, making it suitable for evaluating the carbon cycling and life cycle environmental impacts of mussel aquaculture. By combining carbon flow analysis with LCA, this study aims to characterize the principal carbon pathways associated with DIC related calcification, POC filter feeding, biodeposition and DOC transformation; quantify the allocation of a normalized carbon use basis among carbon removal, storage related pathways, respiration related release and calcification related release; evaluate the environmental impacts of the seed stocking, grow out and harvesting stages; and identify the principal environmental impact categories and contributing production processes. The carbon allocation results are further interpreted to assess whether mussel farming may provide a weak, seasonal and context dependent carbon sink function under favorable environmental conditions. However, the study does not aim to calculate verified net atmospheric CO_2 removal because direct measurements of air–water CO_2 exchange, carbonate system dynamics and long term carbon persistence were unavailable. The results are expected to support low carbon management, process optimization and ecological improvement of mussel aquaculture, while also providing a methodological reference for the integrated assessment of carbon cycling and environmental impacts in shellfish farming systems.

2. Materials and Methods

2.1. Study Area and Research Object

This study focused on typical mussel aquaculture areas in Zhejiang Province, mainly including Ningbo, Zhoushan and Taizhou. These areas have a representative foundation for mussel farming, with diverse water environments and aquaculture practices, making them suitable for assessing carbon cycling and life cycle environmental impacts in mussel aquaculture.

The carbon flow parameters were classified into three types: the normalized accounting basis, literature derived allocation coefficients and conceptual pathways. A scenario based total carbon use basis of 1.45 kg C was adopted for the allocation calculation. The allocation coefficients for carbon removal, carbon storage, respiration related release and calcification related release were obtained from published mussel carbon budget data and were 0.145, 0.673, 0.068 and 0.114, respectively [15]. The original value of 1000 kg CO_2 was retained only as a scenario label in the conceptual diagram and was not used as a physical conversion factor for calculating DIC or the 1.45 kg C accounting basis. DIC associated calcification, POC associated filter feeding, biodeposition and DOC transformation were represented as carbon pathways.

The research object was bivalve mussels. Mussels are typical filter feeding organisms that consume phytoplankton, organic detritus and suspended particles from the water column. Through filter feeding, shell calcification, soft tissue growth, respiration, excretion and biodeposition, mussels retain and redistribute carbon among biological, dissolved and particulate pools [3,6]. These processes may influence local carbon cycling and nutrient dynamics in aquaculture waters. Therefore, this study incorporated carbon source pathways, carbon allocation, release and potential storage related processes into a unified analytical framework. The geographical distribution of the study areas and representative mussel morphology are shown in **Figure 1**. The map covers Ningbo, Zhoushan and Taizhou, while the photographs present the external shell characteristics of the cultured mussels.

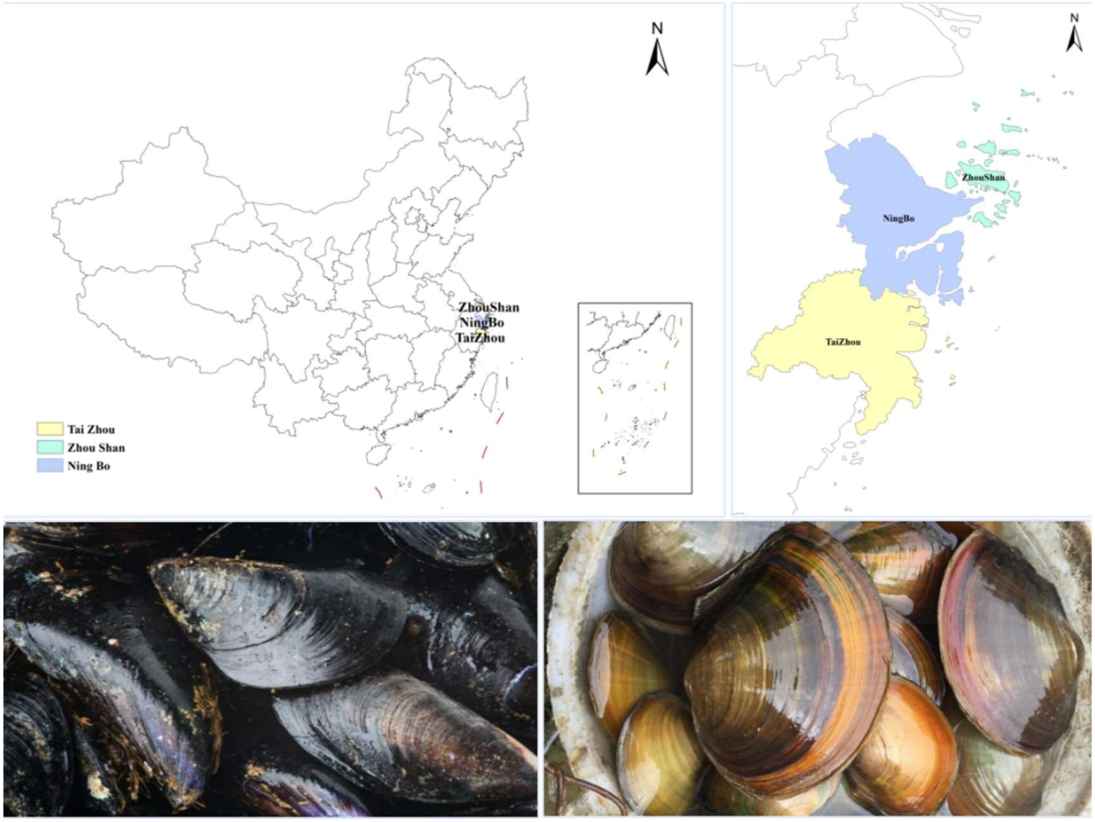

Figure 1. Study area and morphological diagram of bivalves.

2.2. Data Sources for Mussel Aquaculture

The data used in this study, including mussel aquaculture production, farming area, biological carbon content, dry to wet mass ratio and parameters related to carbon cycling, were obtained from published literature, local planning documents, technical specifications and academic databases such as China National Knowledge Infrastructure (CNKI). Relevant findings from previous studies were summarized and selected according to the needs of the present analysis. The production scale and farming area of mussel aquaculture in selected regions of Zhejiang Province are summarized in **Table 1**. The table provides the regional basis for defining the study scope and selecting representative mussel aquaculture systems.

Table 1. Production and farming area of mussels in selected regions of Zhejiang Province.

Region	Aquaculture Type	Farming Area	Production	Data Source
Zhuji City	Freshwater pearl mussel culture, mainly pearl producing mussels	Approximately 200,000 mu	Approximately 36,000 t per year	Reply by Zhuji Municipal Bureau of Commerce to Proposal No. 12 of the Fourth Session of the Fifteenth Zhuji Chinese People's Political Consultative Conference Committee
Yuyao City, Ningbo area	Tidal flat shellfish culture, including mussels	Approximately 20,000 mu	Approximately 5,400 t per year	Yuyao Aquaculture Waters and Tidal Flat Planning
Zhoushan City and Ningbo City, coastal areas	Tidal flat mussel culture	Approximately 80,000 mu	Approximately 18,000 t per year	Zhejiang Seawater Shellfish Production Indicator

Inland areas of Zhejiang Province, including lakes and rivers	Freshwater pearl mussel culture	Approximately 250,000 mu	Approximately 42,000 t per year	Technical Specification for Ecological Culture of Freshwater Pearl Mussels
Zhejiang Province overall	Freshwater mussel and tidal flat mussel culture	Approximately 450,000 mu in freshwater areas and 80,000 mu in tidal flats	Approximately 60,000 t per year	Small Pearl Mussels Linking an Ecological Economy Chain

2.3. LCA Method

LCA is an environmental assessment method that enables systematic tracking and quantitative accounting of a product or process across its full life cycle, from raw resource extraction, material processing and production to use and final disposal [8,9]. This approach is often described as a cradle to grave analysis, and it can be combined with qualitative assessment to evaluate overall environmental performance. The overall LCA framework used in this study is presented in **Figure 2**. The framework links goal and scope definition, inventory analysis and impact assessment with the interpretation of environmental impacts and their potential applications in mussel aquaculture management.

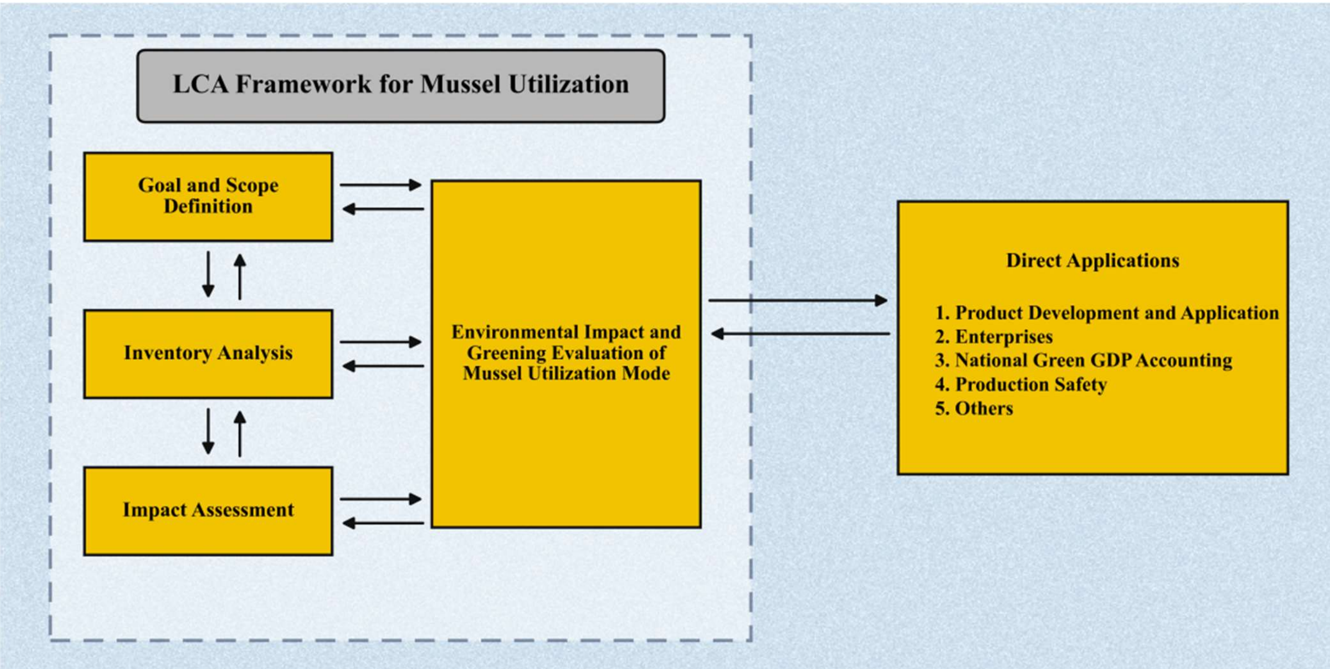

Figure 2. Life cycle assessment framework for mussel aquaculture.

The functional unit was defined as the marketable live weight mussel yield produced from 1 mu of farming area during one complete culture cycle, where 1 mu is equivalent to approximately 666.7 m^2. One functional unit is hereafter referred to as one FU. The corresponding reference flow was the actual mass of marketable live weight mussels harvested from this area during the culture cycle. Marketable live weight included both shells and soft tissues.

As shown in **Figure 3**, the system boundary covered three stages of mussel aquaculture, including seed stocking, grow out and harvesting. The seed stocking stage included seed release and temporary pond preparation; the grow out stage included water pump aeration, water heating, routine inspection, feeding and daily management; and the harvesting stage included harvesting, transportation, cleaning and sorting, and packaging. The detailed process level life cycle inventory corresponding to the defined system boundary, including energy, fuel, material and labor inputs, is provided in **Table S1**.

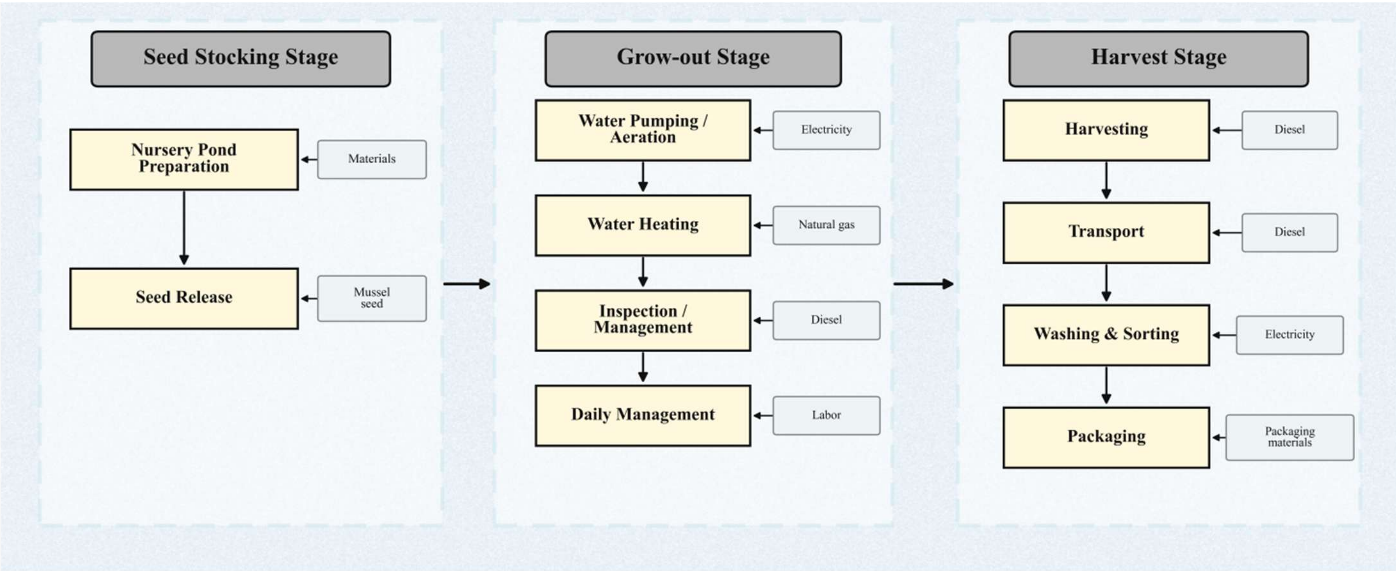

Figure 3. System boundary of the mussel aquaculture life cycle.

The LCA was conducted using the open source Activity Browser software (version 2.11.2; Institute of Environmental Sciences, Leiden University, Leiden, the Netherlands). Eighteen environmental impact categories were quantitatively evaluated using the ReCiPe 2016 v1.03 midpoint assessment method (National Institute for Public Health and the Environment, Bilthoven, the Netherlands) [10,16].The environmental impact categories included terrestrial acidification potential (TAP), global warming potential (GWP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), terrestrial ecotoxicity potential (TETP), fossil resource scarcity potential (FFP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), human carcinogenic toxicity potential (HTPc), human non carcinogenic toxicity potential (HTPnc), ionizing radiation potential (IRP), land occupation potential (LOP), mineral resource scarcity potential (SOP), stratospheric ozone depletion potential (ODP), fine particulate matter formation potential (PMFP), human health related ozone formation potential (HOFP), ecosystem quality related ozone formation potential (EOFP), and water consumption potential (WCP). By comparing the contributions of different processes to each environmental impact category, the main sources of environmental burden within the life cycle of mussel aquaculture were identified. The completely characterized midpoint results for the 18 impact categories and eight production processes are provided in **Table S2**. For the sake of comparing all impacts in the same metric, characterization results would be converted into dimensionless values, called normalization results. In the ReCiPe method, the conversion is conducted according to distance to target [错误!未找到引用源。]. The conversion factors were listed in **Table S4**.

2.4. Carbon Flow Analysis Method

Carbon flow analysis was used to describe carbon allocation and the potential retention and release pathways within the mussel farming system. The revised framework included DIC associated calcification, POC associated filter feeding, carbon removal, storage related pathways, respiration related release, calcification related release, biodeposition and DOC transformation. The value of 1000 kg CO_2 was retained in **Figure 4** only as the scenario basis used in the original conceptual framework.

A scenario based total carbon use basis of 1.45 kg C was adopted for the allocation calculation. The carbon balance was expressed as:

$$C_{use} = C_{removal} + C_{storage} + C_{respiration} + C_{calcification}$$

where C_{use} is the normalized total carbon use basis; $C_{removal}$ represents carbon allocated to removal through harvested biomass; $C_{storage}$ represents the storage related allocation associated with potential biodeposition and DOC related pathways; $C_{respiration}$ represents respiration related carbon release; and $C_{calcification}$ represents calcification related carbon release.

According to published mussel carbon budget data, carbon removal, carbon storage, respiration related release and calcification related release accounted for 14.5%, 67.3%, 6.8% and 11.4% of total carbon use, respectively [15]. DIC associated calcification and POC associated filter feeding were retained as conceptual carbon source pathways but were not assigned separate numerical fluxes. Biodeposits and DOC were represented as potential subpathways associated with the storage related allocation. DOC was further represented as a parent pool containing potential LDOC and RDOC fractions. Because system specific coefficients for DOC production and its partitioning into LDOC and RDOC were unavailable, these subpathways were not separately quantified and were not treated as additional terms in the carbon balance.

3. Results and Discussion

3.1. Carbon Flow Characteristics in Mussel Aquaculture

Figure 4 presents the carbon flow framework of the mussel farming system. A normalized carbon use basis of 1.45 kg C was adopted for carbon allocation analysis. Carbon removal, storage related pathways, respiration related release and calcification related release accounted for 14.5%, 67.3%, 6.8% and 11.4% of the total carbon use basis, respectively. Carbon removal and storage related pathways together represented 81.8% of the allocated carbon, whereas respiration related and calcification related release accounted for 18.2% framework of the mussel farming system. A normalized carbon use basis of 1.45 kg C was adopted for carbon allocation analysis. Carbon removal, storage related pathways, respiration related release and calcification related release accounted for 14.5%, 67.3%, 6.8% and 11.4% of the total carbon use basis, respectively. Carbon removal and storage related pathways together represented 81.8% of the allocated carbon, whereas respiration related and calcification related release accounted for 18.2%. The allocation pattern indicates that a larger proportion of carbon was associated with removal and storage related pathways than with release pathways. This result is consistent with the hypothesis that mussel farming may contribute to local carbon retention and carbon cycle regulation under favorable environmental conditions. However, these results should not be interpreted as direct evidence of net atmospheric CO_2 sequestration. The present analysis did not include measurements of air–water CO_2 exchange, carbonate system dynamics, sediment carbon burial or the long term persistence of organic carbon pools. Therefore, the carbon flow framework is intended to describe potential carbon allocation pathways rather than to quantify verified carbon sink capacity.

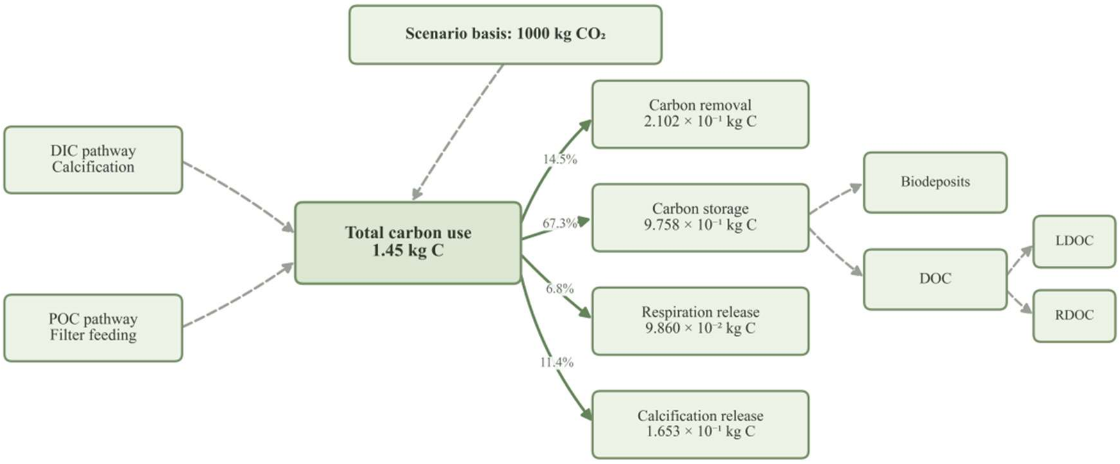

Figure 4. Carbon allocation framework for the mussel farming system.

3.2 Overall Results of Life Cycle Environmental Impacts

Figure 5 shows the relative contributions calculated from the normalized midpoint results. The completely characterized and normalized results are provided in **Tables S2** and **Tables S3**, respectively. TETP contributed the largest share, reaching 35.03% of the total environmental impact. HTPnc and HTPc followed, contributing 22.79% and 18.30%, respectively. Together, these three toxicity related categories accounted for 76.12%, showing that toxicity related impacts were the main contributors to the life cycle environmental burden in this study.

In **Figure 5**, TAP contributed 8.51%, FFP contributed 5.65%, and FETP contributed 4.89%, while the remaining categories together contributed 4.84%. This pattern suggests that the environmental burden of mussel aquaculture was not mainly driven by a single climate related category, but was more closely related to ecotoxicity, human health impacts, acidification and fossil energy use. Similar LCA studies on aquaculture and bivalve shellfish production have also emphasized that energy use, fuel consumption, infrastructure and farm management can strongly influence environmental impact results [错误!不能识别的开关参数。,错误!不能识别的开关参数。].

These results show that mussel aquaculture has both potential ecological functions and production related environmental burdens. On the one hand, harvested carbon removal, storage related allocation, POC filter feeding, biodeposition and DOC associated pathways may contribute to local carbon retention and carbon cycle regulation. On the other hand, facility operation, fuel use and management activities generate environmental burdens that cannot be ignored. Therefore, evaluating mussel aquaculture solely from the perspective of biomass carbon retention would lead to an incomplete assessment.

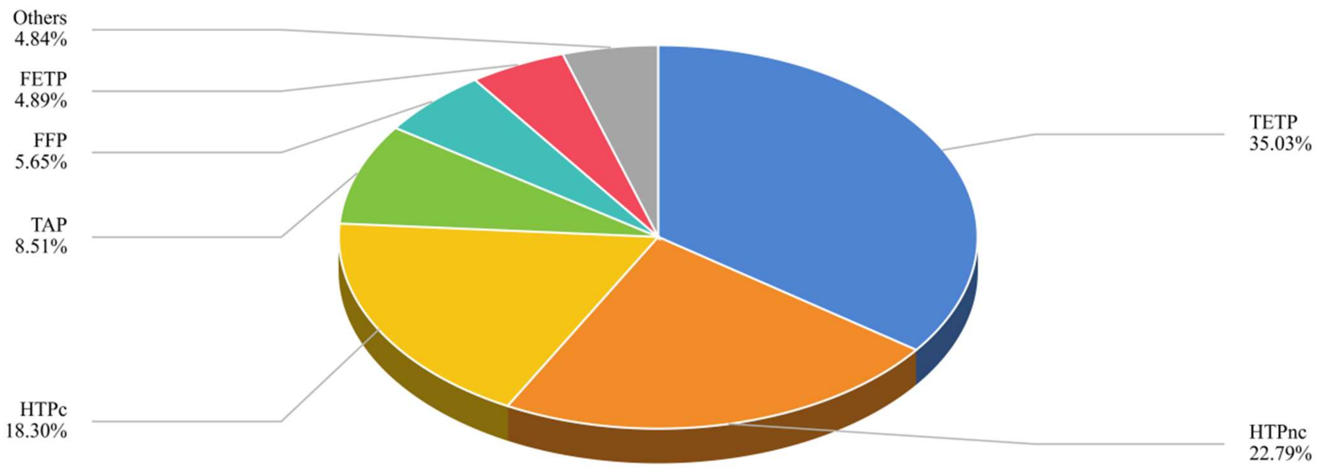

Figure 5. Relative contributions of environmental impact categories in the mussel aquaculture life cycle.

3.3. Monetized Environmental Impact Results

Figure 6 presents the monetized environmental impacts of the different environmental impact categories per functional unit. HTPnc generated the highest monetized environmental impact, reaching 46.5922 RMB/FU. FFP ranked second at 29.5355 RMB/FU, followed by TAP at 13.0190 RMB/FU, GWP at 10.4003 RMB/FU and PMFP at 8.9989 RMB/FU. Together, these five categories accounted for 108.5459 RMB/FU, corresponding to 96.45% of the total monetized environmental impact. The remaining impact categories showed considerably lower monetized values.

The comparison between **Figure 5** and **Figure 6** shows that the ranking of environmental impact categories changed after monetization. TETP had the largest relative contribution in the normalized midpoint results shown in **Figure 5**, whereas HTPnc and FFP dominated the monetized results in **Figure 6** TAP, GWP and PMFP also made substantial monetary contributions. This difference reflects the influence of the characterization, normalization and monetization procedures. Monetized environmental impact assessment provides an integrated monetary representation of potential environmental damage, but it should be interpreted together with midpoint impact results rather than used as a substitute for them.

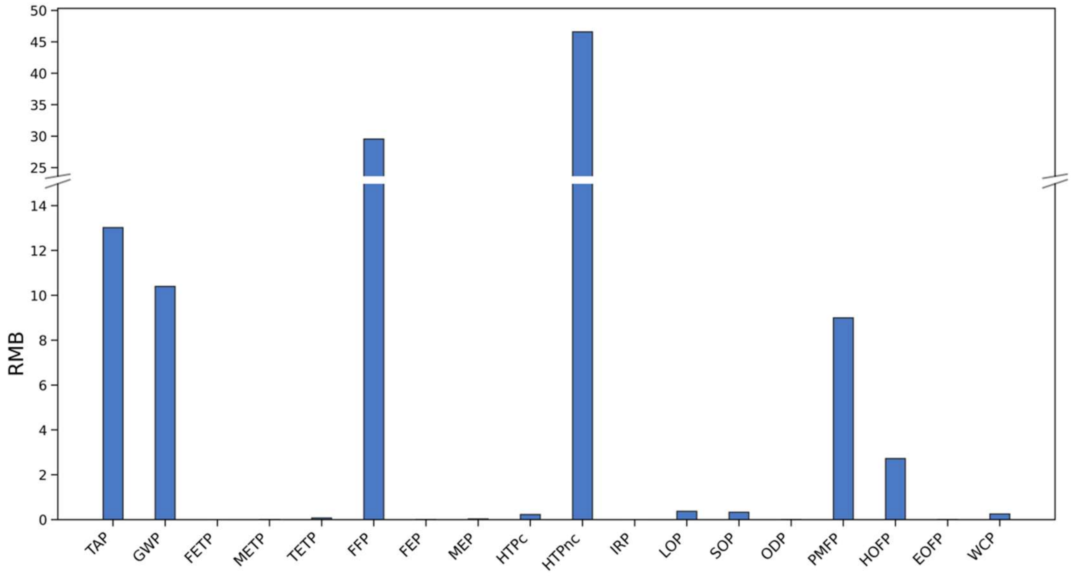

Figure 6. Monetized environmental impacts by impact category.

3.4. Contribution Analysis of Different Production Processes

Figure 7 compares the contributions of different production processes to each environmental impact category. The environmental burden was not concentrated in one single operation, but was mainly distributed across temporary pond preparation, facility operation during the grow out stage, and harvesting activities. Among all processes, water pump aeration, harvesting, temporary pond preparation, routine inspection and feeding, and water heating were the most important contributors.

For TETP, **Figure 7** shows that water pump aeration made the largest contribution, accounting for 40.26%. Harvesting and temporary pond preparation contributed 25.70% and 20.32%, respectively. This pattern suggests that continuous facility operation during the grow out stage and mechanical activities during harvesting were the main sources of terrestrial ecotoxicity. For HTPnc, temporary pond preparation contributed 47.70%, while harvesting contributed 30.53% and water pump aeration contributed 9.40%. This result means that facility preparation before seed stocking, together with related material and energy inputs, should not be treated as a low impact process.

For HTPc, water pump aeration contributed 37.78%, harvesting contributed 26.33%, temporary pond preparation contributed 13.05%, and routine inspection and feeding contributed 12.97%. These results show that electrically powered facility operation, mechanical harvesting and routine management jointly shaped this category of environmental burden. In terms of resource consumption and acidification, harvesting was the leading contributor to TAP and FFP, contributing 28.02% and 43.99%, respectively. Routine inspection and feeding also contributed 32.32% to FFP, reflecting the role of diesel and other fossil energy inputs in resource related impacts.

For FETP, routine inspection and feeding contributed 31.97%, water pump aeration contributed 29.17%, and temporary pond preparation contributed 20.88%. These results show that aquaculture management and facility operation played important roles in freshwater toxicity related impacts. Overall, **Figure 7** highlights three major control points for environmental optimization: reducing the energy demand of water pump aeration, improving harvesting and inspection practices, and optimizing temporary pond preparation.

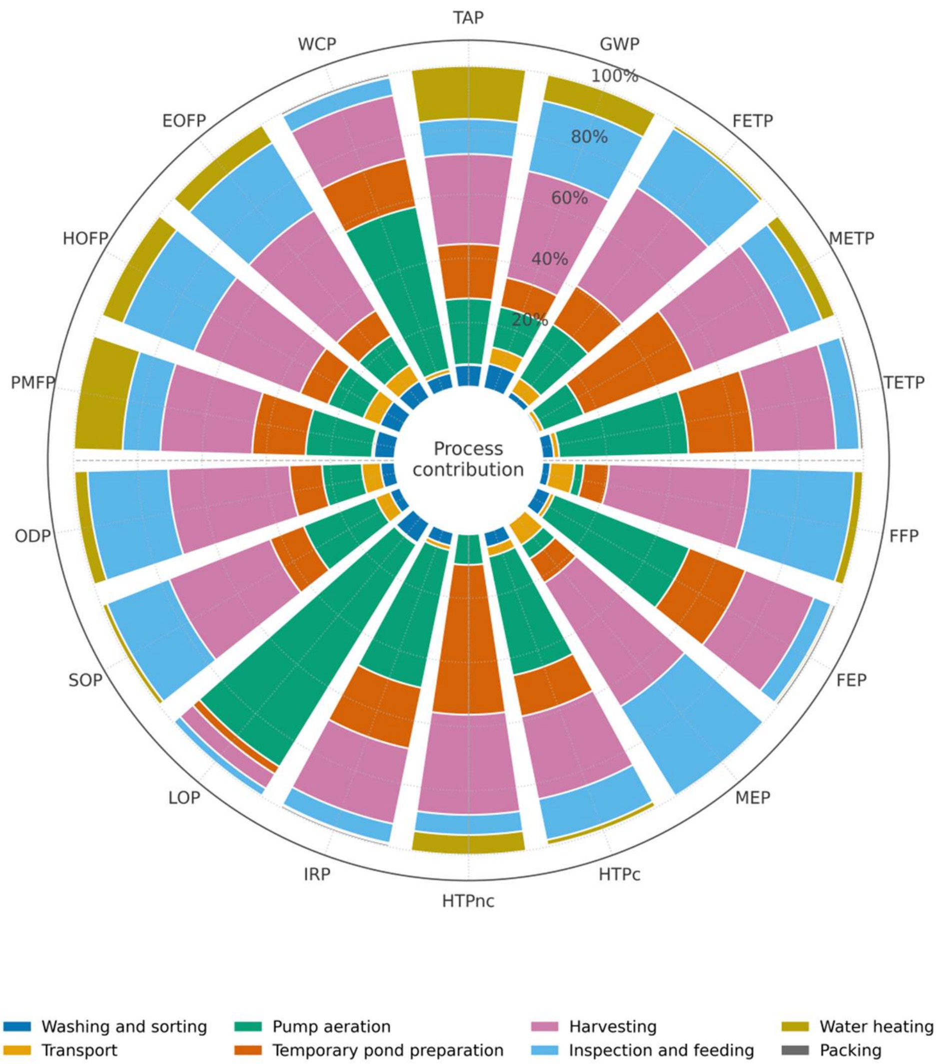

Figure 7. Contributions of Various Production Processes to Environmental Impact Categories.

3.5. Discussion

The results from **Figure 4** to **Figure 7** show that mussel aquaculture should be understood as a system with both carbon cycling functions and production related environmental burdens. The carbon flow framework allocated a larger share of the scenario carbon use basis to harvested carbon removal and storage related pathways than to respiration and calcification related release. DIC associated calcification and POC associated filter feeding were retained as conceptual source pathways, while biodeposits, DOC, LDOC and RDOC were used to illustrate potential transformation pathways rather than independently quantified carbon pools.

This allocation pattern is consistent with the possibility that mussel farming may contribute to local carbon retention under favorable environmental conditions. However, the adopted coefficients were derived from published carbon budget data rather than site specific field measurements. Furthermore, shell carbon, harvested tissue carbon, biodeposits and DOC related carbon cannot automatically be equated with atmospheric CO_2 removal. Respiration, calcification, remineralization, downstream product fate and air–water CO_2 exchange may all influence the net ecosystem carbon balance. The present model therefore provides indirect support for a potential weak and context dependent carbon sink function, but it does not independently establish a net atmospheric CO_2 sink.

The LCA results further show that the ecological role of mussels does not automatically translate into low environmental impact across the whole production chain. In **Figure 5**, TETP, HTPnc and HTPc dominated the proportional environmental impact results, while **Figure 6** showed that HTPnc and FFP were more important after monetization. This difference means that impact proportions and monetized environmental impacts describe different aspects of environmental performance. Proportional results are useful for identifying dominant impact categories, whereas monetized results provide an integrated estimate of environmental damage. Therefore, the two types of results should be interpreted together rather than treated as interchangeable.

The process contribution results in **Figure 7** provide a more practical explanation for these patterns. Water pump aeration was the main contributor to several toxicity related categories, suggesting that continuous facility operation during the grow out stage was a key environmental pressure. Harvesting also contributed strongly to TAP and FFP, reflecting the influence of diesel use and mechanical operations. Similar mussel LCA studies have found that vessel operation, energy demand and processing activities can become major sources of environmental impact, especially when fuel and electricity use are included in the system boundary [19,20]. This is consistent with the present results, where energy related processes were closely linked with both resource consumption and human health related impacts.

Another important issue is the potential redistribution of organic matter caused by mussel filtration and biodeposition. While filtration can improve water clarity and remove suspended particles, biodeposits may increase sedimentation and organic matter accumulation beneath or near culture areas [21,22]. Under certain hydrodynamic conditions, this can change sediment oxygen demand, nutrient fluxes and benthic community structure [错误!不能识别的开关参数。]. Therefore, the environmental performance of mussel aquaculture depends not only on production inputs but also on the capacity of the receiving water body to disperse and assimilate biodeposits. For this reason, site selection, stocking density and water exchange conditions should be considered together with energy management when optimizing mussel farming systems.

Overall, this study suggests that future improvement should focus on three linked aspects. First, the energy efficiency of water pump aeration and water heating should be improved, because these processes are closely related to toxicity and resource related impacts. Second, harvesting and routine inspection should be optimized to reduce diesel consumption and associated emissions. Third, temporary pond preparation should be further assessed because it made a large contribution to HTPnc, suggesting that material inputs and infrastructure related processes may have been underestimated in conventional evaluations. In addition, long term monitoring of DOC, RDOC and LDOC dynamics is needed to test whether the potential refractory organic carbon pathway represented in the model can be maintained under field conditions. Combining process optimization with carbon flow monitoring would allow mussel aquaculture to retain its ecological functions while reducing life cycle environmental burdens.

4. Conclusions

This study combined carbon flow analysis with LCA to evaluate carbon cycling and environmental impacts in typical mussel aquaculture systems in Zhejiang Province. Using a scenario based total carbon use basis of 1.45 kg C, 0.21025 kg C was allocated to harvested carbon removal, 0.97585 kg C to storage related pathways, 0.09860 kg C to respiration related release and 0.16530 kg C to calcification related release. Harvested carbon removal and storage related allocation together accounted for 81.8% of the scenario basis, whereas the two release terms accounted for 18.2%.

These findings suggest that mussel farming may contribute to local carbon retention and carbon cycle regulation and may exhibit a weak, context dependent carbon sink function under favorable conditions. However, the present study did not measure air–water CO_2 exchange, total alkalinity, pCO_2, sediment remineralization, carbon burial or the long term persistence of organic carbon pools. The calculated allocation therefore cannot be directly converted into net atmospheric CO_2 sequestration.

The life cycle environmental impact results showed that the environmental burden of mussel aquaculture was mainly concentrated in toxicity related categories. TETP contributed the most, accounting for 35.03%, followed by HTPnc and HTPc, which accounted for 22.79% and 18.30%, respectively. In addition, TAP, FFP and – FETP accounted for 8.51%, 5.65% and 4.89%, respectively, while the remaining impact categories together accounted for 4.84%. These results show that although mussel aquaculture may provide carbon retention and aquatic carbon cycle regulation functions, its life cycle environmental impacts are still influenced by energy consumption, facility operation, fuel use and production management.

The monetized environmental impact results showed that HTPnc made the largest contribution, reaching 46.5922 RMB/FU. It was followed by FFP, TAP, GWP and PMFP, with values of 29.5355, 13.0190, 10.4003 and 8.9989 RMB/FU, respectively. These five categories accounted for 96.45% of the total monetized environmental impact. The ranking of the normalized midpoint contributions differed from that of the monetized results, indicating that environmental performance should be evaluated using both midpoint impact indicators and monetary valuation rather than relying on a single assessment metric.

According to the life cycle assessment results, environmental optimization of mussel aquaculture should focus on energy consumption, facility operation and harvesting activities. First, the operating efficiency of water pump aeration and water heating equipment should be improved to reduce continuous energy consumption during the grow out stage. Second, harvesting, transportation, routine inspection and feeding practices should be optimized to reduce the use intensity of fossil energy such as diesel, thereby lowering impacts related to fossil resource scarcity, global warming and terrestrial acidification. Third, the material and energy inputs during temporary pond preparation should be further reviewed and optimized to reduce their contribution to health related impact categories such as HTPnc.

At the industrial management level, a life cycle environmental impact accounting system for mussel aquaculture should be established. Energy use, facility materials, harvesting and transportation, and packaging processes should all be included in environmental management. Policy support could encourage farmers to adopt energy saving equipment, cleaner energy and more efficient harvesting methods, while also promoting standardized and refined management of aquaculture processes. Through production process optimization and policy guidance, mussel aquaculture can further improve its low carbon and ecological performance while maintaining its functions in filter feeding, water purification and carbon cycle regulation.

This study analyzed carbon cycling and environmental impacts in mussel aquaculture based on the current carbon flow diagram and life cycle inventory data, but some limitations remain. First, part of the carbon flux data came from model settings and still needs to be verified through field measurements. The carbon flow model did not include direct measurements of air-water CO_2 exchange, total alkalinity, calcification related CO_2 release, sediment remineralization, or the long term persistence of RDOC. Therefore, the calculated carbon retention cannot be directly converted into net CO_2 sequestration. Second, the study focused on a typical mussel aquaculture process and did not fully compare differences in environmental impacts among different water-body types, stocking densities, aquaculture models, and management practices. Third, the life cycle assessment results were affected by the completeness of the inventory data and the assessment method used; therefore, data accuracy should be further improved in future research.

Future studies should strengthen field monitoring of air–water CO_2 exchange, DIC, total alkalinity, pCO_2, calcification, respiration, POC ingestion, biodeposition, DOC production, LDOC and RDOC persistence, sediment remineralization and energy consumption. Future studies should also integrate carbonate system measurements, organic carbon degradation experiments, and full life cycle greenhouse gas emissions to determine whether mussel aquaculture acts as a net source or sink of atmospheric CO_2. Comparative studies under different aquaculture models and regional conditions should also be carried out to improve the evaluation system for carbon cycling and life cycle environmental impacts in mussel aquaculture. In future management, potential carbon retention functions should be considered together with environmental burden control, so that mussel aquaculture can shift from a production oriented model toward a lower carbon, more ecological, and sustainable development pathway.

Supplementary materials: Table S1: Life cycle inventory. Table S2: LCA results. Table S3: Normalized LCA results. Table S4: Normalization Factor. Table S5: Monetization Factor.

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