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Global Warming Potential and Waste Handling of Pearl Farming in Ago Bay, Mie Prefecture, Japan

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Abstract: Pearl farming (PF) represents a significant portion of the world's total aquaculture production and is a growing multibillion-dollar sector of mollusk aquaculture. However, PF in Mie Prefecture, Japan, has resulted in the deterioration of environmental conditions in Ago Bay, and its environmental impacts are yet to be evaluated using a life-cycle assessment (LCA). Thus, in this study, a cradle-to-gate LCA using 1 kg of pearl produced in Ago Bay was conducted. The key results showed that the global warming potential (GWP) was equivalent to 4.98 kg CO_2, which is lower than the GWPs of metals, such as gold and silver, commonly used in jewelry production. Meanwhile, the waste handling of PF is progressing, with current efforts being focused on extracting calcium carbonate, exporting shell waste, and reducing plastic waste. These findings provide critical insights for achieving sustainable pearl production aquaculture.

Keywords: environmental impacts; resource management; sustainable aquaculture; life-cycle assessment; Japan

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1. Introduction

Pearl farming (PF) is a growing multibillion-dollar sector of mollusk aquaculture [1], which has progressively increased its contribution to the economic development of the aquaculture sector while showing excellent potential for progress [2]. Global demand for pearls has significantly benefited the economic growth of countries as either producers or suppliers of pearls. For instance, Japan has exported USD 332 million worth of worked pearls (e.g., necklaces and other pearl-made jewelry) in 2017, the value of which has roughly doubled since the 2008 global financial crisis [3]. Other countries that have gained significant economic benefits from PF include Australia and French Polynesia, with the former being the major global producer of South Sea pearls and the latter being the primary global supplier of Tahitian black pearls [4].

The success and relevance of PF can be attributed to the constant demand for pearls in the global jewelry industry [5], which is predicted to grow to approximately USD 25 billion by 2030 [6]. Pearls are considered the oldest type of gemstone on Earth [6] and are known as the queen of jewels, symbolizing material wealth throughout human history [7]. For instance, during the reign of the Byzantine Empire, only emperors were entitled to wear these precious gems [8]. Furthermore, in England, royals were seen wearing pearl jewelry and clothing ornamented with pearls as symbols of the upper class during the 16th century (also known as the Pearl Age) [9]. Although pearl jewelry has seen an overall decline (in the 17th to 18th centuries) and an increase (in the 19th to 20th centuries) in popularity, it should be noted that pearls have been a substantial part of jewelry history [8]. To date, pearls, particularly those that are cultured, remain significant within jewelry culture [10].

In their long history of being favored as adornments and pieces of expensive jewelry, pearls have experienced an evolution in their harvesting methods, from natural and by-chance harvesting to modern cultured PF [7]. For example, in Japan, the transition from natural to cultured PF stemmed from the collapse of mother-of-pearl Akoya oysters due to the overexploitation of natural pearls, which are valued at very high prices [10]. Thus, several attempts have been made to artificially culture Akoya oysters to increase their population [10]. Notably, the foundation of cultured PF techniques proposed by Kokichi Mikimoto in the 19th century has since been improved upon [10] and has consequently led Japan to become a major center of the global culture pearl trade [11].

However, as the science and technology of PF have advanced, environmental impacts have also increased. These include oil spills during operations, water pollution owing to the application of chemicals, and marine pollution from the use of plastics and other materials required for PF [5]. In Australia, workshops composed of pearl industries and stakeholders were held in 2001 and 2004 to assess the environmental risks (e.g., water quality loss from hydrocarbon spills), eventually leading to the development of environmental management plans [12]. Meanwhile, in Asia, China and Japan are among the countries experiencing substantial adverse environmental impacts from PF [12]. For example, in China, PF was temporarily banned in Hubei Province in 2007 because of concerns regarding the excess use of fertilizers [13]. Furthermore, in Japan, organic and nitrogen inputs in PF have been reported to impact the dissolved oxygen content of bottom water as well as the sulfide content of sediment, which could in turn influence macrobenthic assemblages [14].

Therefore, sustainable PF practices are required to reduce environmental degradation. It is critical to manage farms sustainably by accurately understanding their production capacity while effectively preventing the deterioration of pearl farms and the generation of hydrogen sulfide [15]. In addition, if PF is performed sustainably, it has the potential to contribute profitably to environmental remediation [16] and provide indications of ecological stress [13]. To achieve this goal, it is important to first assess the environmental impacts of current PF to effectively design and/or implement the necessary adjustments to reduce environmental pressure. One way to assess these impacts is through the application of a life-cycle assessment (LCA), which method has been widely used to evaluate the impact of the aquaculture industry on the environment [17–19].

In this study, we utilized the LCA methodology to evaluate the environmental impacts of PF in Ago Bay, Japan. In summary, PF in Ago Bay has previously been found to have resulted in the deterioration of the environmental conditions of the bay [20], for instance, by increasing nutrient inputs [21]. Based on our extensive literature review, the application of the LCA framework has not yet been performed for the bay; therefore, this study is the first to do so. Specifically, we aimed to quantify the global warming potential (GWP) of PF production, which is critical in the era of climate change. PF and climate change have a two-way relationship: the former potentially contributes to the latter through greenhouse gas (GHG) emissions (e.g., during operations) [17], while the latter influences the former, for instance, through the reduced growth and biomineralization capacity of pearl sacs due to increasing sea temperature [22]. Thus, the results of this study can be used to inform the PF industry and stakeholders in Ago Bay in terms of climate-change-resilient PF techniques. Considering that PF is an important economic and cultural asset of the bay, it is critical to identify its impacts while proposing suggestions and/or developing frameworks to maintain the sustainability of the PF industry [23].

2. Materials and Methods

2.1. Study Site

This study was conducted to evaluate the environmental impact of PF in Ago Bay, which is located in Ise-Shima National Park on the Shima Peninsula, Mie Prefecture, Japan (Figure 1). This bay is a suitable location for PF considering its enclosed topography, where the ria coastline protects against the intrusion of ocean waves from the sea [20]. Furthermore, the bay has a long and world-renowned history of pearl culture (of more than 100 years) [20]. Since the establishment of pearl aquaculture in the early 1890s [24], pearl production in Mie Prefecture has dominated the Japanese market, with exports to the international market having expanded [21]. Eventually, over time, this industry has resulted in the deterioration of the environmental conditions of the bay, including a decrease in sediment quality and dissolved oxygen in the bottom water [20]. Meanwhile, increases in nutrients, such as nitrogen and phosphorus, that favor algal growth have also been documented in the bay, resulting in harmful algal blooms that cause the mass mortality of pear oysters [21]. To reduce and/or address environmental degradation, a restoration project was launched in Ago Bay in 2009 [21]. To date, scientific investigations have been undertaken here aiming to contribute to its management, such as the works of Toyoshima et al. [24] and Murata et al. [25]. These aimed to assess the effectiveness of satoumi activities and evaluate aquaculture facilities for the sustainable use of coastal resources, respectively. Similarly, this study aimed to indirectly contribute to coastal resource management in Ago Bay by conducting an LCA of the PF.

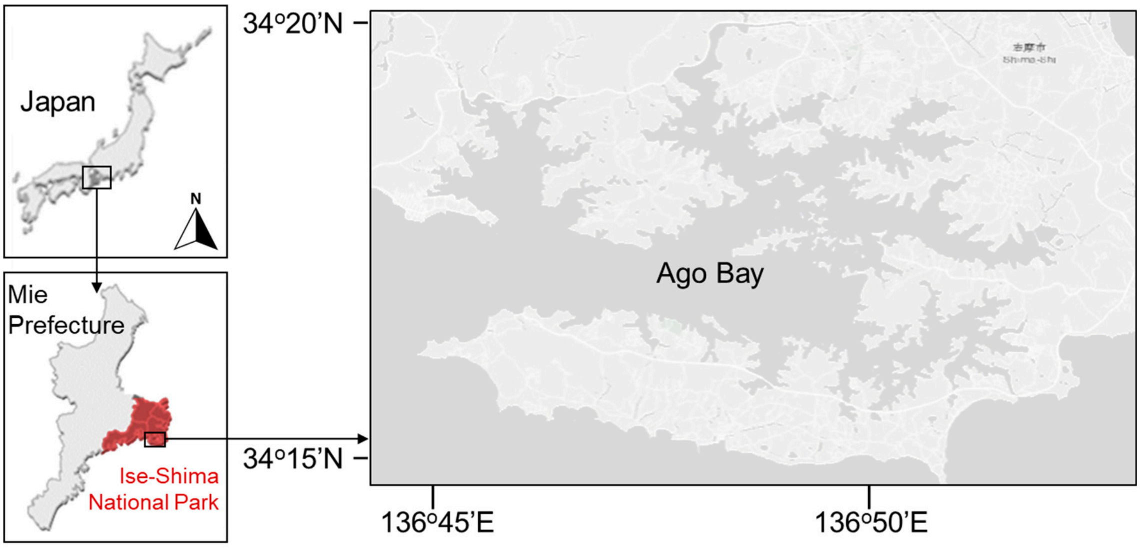

Figure 1. Location map of Ago Bay, Ise-Shima National Park, Mie Prefecture, Japan.

2.2. LCA Framework

In this study, we conducted an LCA, which is a methodology used to evaluate the environmental impacts of a process or product within specific boundaries and throughout its entire life cycle, for instance, from the extraction of raw materials to various end-of-life scenarios (e.g., disposal and recycling) [17]. The LCA methodology has been widely used and standardized by international organizations, such as the International Organization for Standardization (ISO) [26] and the Society of Environment Toxicology and Chemistry (SETAC) [27]. This framework consists of four stages, including (Section 2.2.1) goal and scope definition, (Section 2.2.2) life-cycle inventory, (Section 2.2.3) life-cycle impact assessment, and (Section 3) the interpretation of results. These steps are described in the following sections.

2.2.1. Goal and Scope Definition

The environmental impacts of pearl production under open farming conditions in Ago Bay, Japan, were quantified using an LCA based on ISO standards 14040 and 14044, which are widely recognized standards for LCA studies (ISO 14040 and ISO 14044). The functional unit of this study was 1 kg of pearls, which is the primary unit in the distribution of pearls to the market from Ise-Shima National Park.

The cradle-to-gate system boundary (Figure 2) covers the five main production stages of PF: hatching, a floating–upwelling system (FLUPSY) for raising spats, grafting, grow-out, and harvesting. Material and energy resource inputs for each process are also included. These materials include wood for rafts, rope, rubber, and plastic products. However, other stages, such as growth, require boats to monitor the growth of grafted oysters. Furthermore, gasoline and engine oil were also considered here, in addition to the use of electricity in hatcheries. The three outputs of the PF considered here were pearls as the main products, emissions to the biosphere (with a focus on GWP), and byproducts or waste. In PF, meat and shells are considered waste, along with all defective pearls. However, these by-products can also be recycled and utilized for other purposes. Although the LCA analysis was limited to the GWP of PF, the waste handling of defective pearls, oyster shells, and plastics was included in this discussion. The distribution, purchasing, and consumption phases were also excluded due to a lack of reliable data.

2.2.2. Life-Cycle Inventory

This study analyzed all the relevant inputs associated with PF. Primary data were collected from interviews with key informants from the Tategami area pearl association, comprising experienced pearl farmers, conducted in December 2021. A single producer can harvest 80,000 pearls (48 kg) per year. Using a functional unit of 1 kg of pearls, the following inputs (Table 1) were subsequently derived and estimated from the interviews.

Table 1. Inventory of the main inputs of pearl farming in Ago Bay, Mie Prefecture, Japan. All inputs are referred to in terms of 1 kg of pearls harvested.

Inputs	Value
Materials and fuel	
High-density polyethylene (HDPE)	8
Polyvinyl chloride (PVC)	0.8
Rubber	0.1
Concrete (kg)	0.6
Wood (m^3)	102
Fuel (l)	45
Engine oil (l)	0.4
Energy	
Electricity (kWh)	0.5
Resources	
Seawater (m^3)	2.12
Freshwater (m^3)	0.1

2.2.3. Life-Cycle Impact Assessment (LCIA)

The environmental impacts of pearl production were quantified using multiple-interface life-cycle assessment (MiLCA) software. MiLCA software is a support system that enables researchers to perform basic calculations required for LCA, including inventory analysis and impact assessment [28]. The data for the MiLCA software were aggregated and then averaged from the data collected during the interviews.

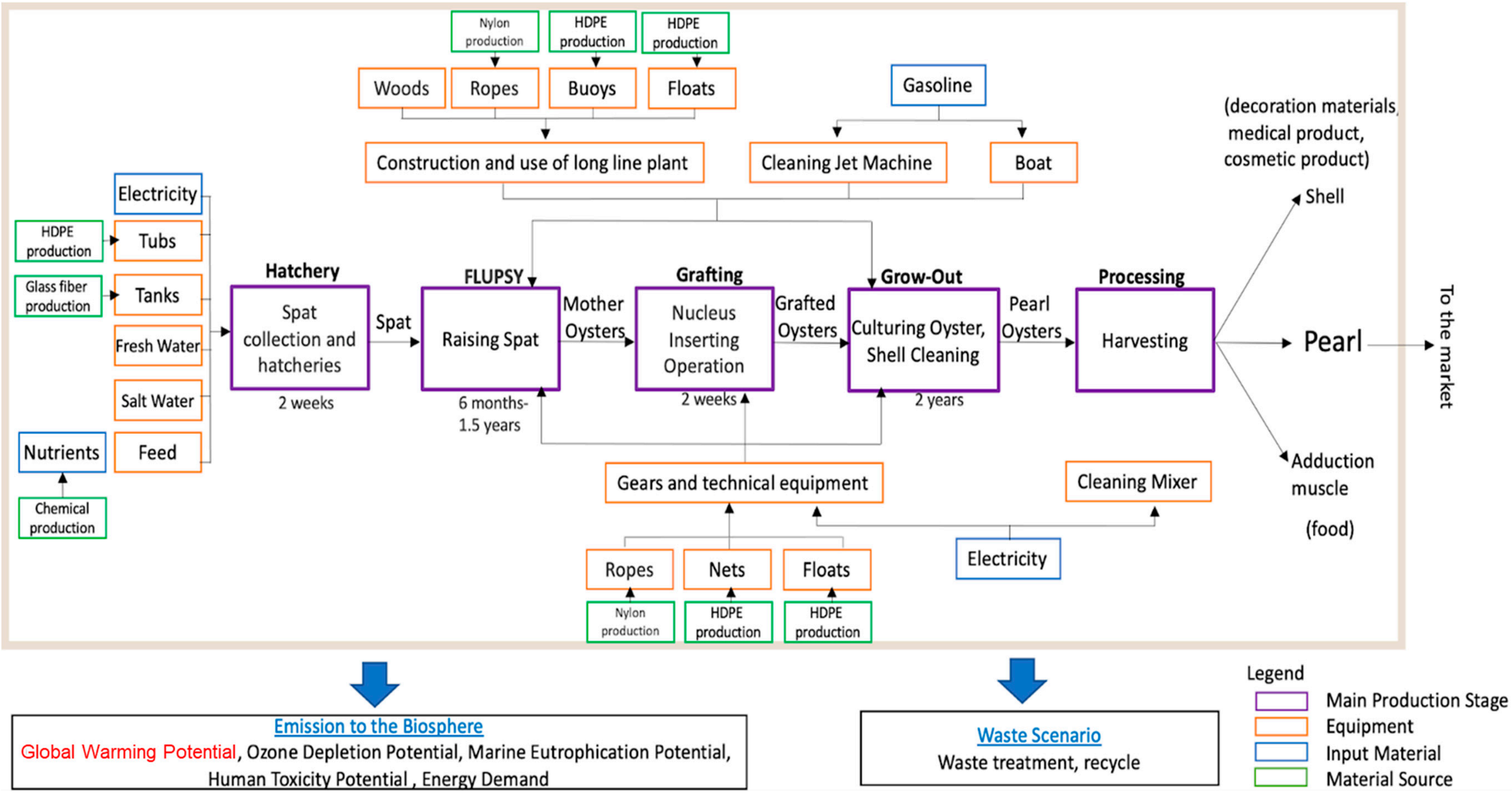

Figure 2. System boundary used in the life-cycle assessment (LCA) of pearl farming (PF) in Ago Bay, Mie Prefecture, Japan. Due to a lack of available data, this analysis was limited to the global warming potential of pearl farming (colored red) due to emissions to the biosphere.

3. Results and Discussion

As shown in Figure 2, this study has three main points of discussion. The global warming potential (GWP) of PF is presented in Section 3.1, which highlights the potential GHG emissions from 1 kg of harvested pearls. We compared the GWP of pearls with the GWPs of other commonly used metals in jewelry production, such as gold and silver, as discussed in Section 3.2. Finally, the handling of solid waste, from defective pearls to plastic waste, is presented in Section 3.3.

3.1. Life-Cycle Impact Assessment

The emissions generated by 1 kg of PF production were as follows: 1.1×10^{-1} kg of carbon dioxide (CO_2), 5.1×10^{-2} kg of methane (CH_4), and 1.3×10^{-2} kg of nitrous oxides (N_2O), as shown in Table 2. The GWP for producing 1 kg of pearls was equivalent to 4.98 kg of CO_2. This was derived using the IPCC (2013) 100-year GWP factors of 265 and 28 for N_2O and CH_4, respectively, which were equivalent to 1 kg of CO_2 (CO_2eq).

Table 2. Greenhouse gas emissions and corresponding global warming potential values for 1 kg of pearls harvested from Ago Bay, Ise-Shima National Park, Japan.

Greenhouse Gas	Emission Values (kg)	Global Warming Potential Values (kg CO_2eq)
Carbon dioxide (CO_2)	1.1×10^{-1}	0.10
Methane (CH_4)	5.1×10^{-2}	1.43
Nitrous oxides (N_2O)	1.3×10^{-2}	3.45
Total global warming potential		4.98

The analysis showed that most greenhouse gas emissions were generated from the fuel consumed during the production stage. Fuel combustion is considered one of the main contributors to the environmental impact of oyster production [18]. The highest fuel consumption was documented during the "grow-out" stage, which was responsible for approximately 90% of the total fuel consumption (Figure 3). As shown in Figure 2, the grow-out stage could span 2 years, while the operation to be maintained during this phase requires high fuel consumption. Cartier [29] previously noted that the regular cleaning of oysters and nets is required to maintain healthy growth, which is the most labor-intensive phase of PF. There is also a trend in which different grow-out strategies are being undertaken to improve pearl quality [29], which in turn requires high fuel consumption. Clearly, the grow-out stage of PF consumes a high volume of fuel. Looking at other grow-out stages, for instance, high diesel consumption is needed in salmon aquaculture to power up the equipment used in this stage [19].

Figure 3. Fuel consumption during production for a single pearl farm in Ago Bay, Ise-Shima National Park, Mie Prefecture, Japan.

To our knowledge, this is the first LCA study to generate the GWP of a PF. Other related LCA studies have previously focused on the bivalve aquaculture of oysters (e.g., [17]) and clams (e.g., [18]). Both of these studies indicated that fuel combustion, in the form of carbon dioxide emissions, was among the main contributors affecting the environment. However, these studies also highlighted that bivalve aquaculture could have a positive environmental impact. Tamburini et al. [17] highlighted that the impact of climate change on oyster production was less than that on fish aquaculture, indicating that oyster production is more sustainable. Meanwhile, Turolla et al. [18] argued that clam aquaculture contributes to carbon sequestration and eutrophication reduction. Although the values from these studies and those generated in the present study (Table 2) are not comparable, owing to the differences in functional units used, overall, PF and other bivalve aquacultures are more sustainable compared to other types of aquaculture (e.g., fish and shrimp aquaculture) [30].

3.2. Comparing the Global Warming Potential of Pearls with Other Jewelries

The constant demand for pearls in the global jewelry industry is predicted to increase further by 2030 [5,6]. This demand has raised concerns about the long-term effects on the environment, given that PF has been documented to produce environmental impacts, such as eutrophication, pollution, and the introduction of invasive species (e.g., [31–33]). However, several other studies have argued that PF has positive impacts and is more sustainable than other jewelry production methods (e.g., [30,34,35]). Thus, this study also aimed to contribute to this discourse by comparing the results of the LCIA, specifically the GWP of PF, with those of other jewelry products and/or commonly used metals in jewelry production (Table 3).

Table 3. Global warming potential (GWP) of jewelry production.

Type of Jewelry (1 kg)	GWP (kg CO_2 Equivalent)	Data Source
Pearls	4.98	This study
Diamonds	545,200	[36]
Gold	31,000	[37]
Silver	206	[38]
Platinum	12,500	[39]
Tungsten	12.6	[39]
Titanium	8.1	[39]

Table 3 shows that the GWP of PF was less than the GWPs for other types of jewelry production. For instance, considering the common metals used in jewelry production, such as gold and silver [40], their GWPs—31,000 and 206 kg CO_2 equivalent, respectively—are comparatively larger. Similarly, the GWPs of platinum (12,500), tungsten (12.6), and titanium (8.1) are all larger than that of pearls (4.98). The common and main contributors to the high GWPs of these metals occur during the mining and refining stages [37–41]. During the extraction of these metals, significant energy is used, for instance, for equipment and transportation [39,42]. Meanwhile, the refining and processing stages equally demand high energy consumption [41]. Contrastingly, pearl production consumes less energy, as reflected in this study. For instance, in comparison to the extraction and refining processes of metals, the harvesting of pearls does not require industry-grade machinery.

Overall, PF is considered to have a low environmental impact and effectively provides socioeconomic benefits [33,34]. In the context of sustainable production, PF is considered a more sustainable method for meeting global demands in the jewelry and fashion industries [30,35]. In the broader aquaculture context, oyster production is also more sustainable than fish production [17]. It should be noted, however, that we only discuss here the GWP of PF; other environmental impacts, such as biodiversity loss and marine pollution, were excluded from this study. However, to give context to the potential effect of PF on biodiversity, Cartier and Carpenter [34] highlighted that PF has a slightly positive effect on fish biodiversity due to the indirect contributions of PF, such as shelter benefits. Thus, further investigations are necessary to compare PF with the processing of other commonly used metals in jewelry production in these contexts to provide a more holistic interpretation of PF as a sustainable form of aquaculture [43–45].

3.3. Solid-Waste Handling in Pearl Farming

3.3.1. Defective Pearls

In 2021, the key informant interview revealed that, on average, one pearl farm at the study site could produce 80,000 pearls. However, approximately 40% of the production is considered suitable for sale at high prices, while the remaining 60% are sold at lower prices and/or categorized as defective pearls. Defective pearls generally go to auctions as they are considered to have lower values owing to their imperfections, such as irregularities in shape, size, or color (Figure 4). When these flaws occur, the defective pearls are sold at a lower price and are often not sold at all. However, several farmers shared that collectors and artists have sought pearls with unique or unusual deformities. There is uncertainty in producing defective pearls; thus, in general, pearl farmers aim to produce high-quality pearls, which in turn increases their value [46]. As previously highlighted by Cartier [29], any substantial improvement in the quality of harvested pearls will result in higher incomes for pearl farmers. Thus, to date, there have been many investigations into improving pearl quality (e.g., [47–49]).

Figure 4. Examples of defective pearls: not round enough and too small. This photo was taken by the first author in one of the pearl shops in Ago Bay, Ise-Shima National Park, Mie Prefecture, Japan.

We also documented from pearl farmers that unsold defective pearls can be processed into calcium carbonate sources and subsequently traded as raw materials for skin care, other cosmetic products, and medicinal purposes. This is common, considering that pearl powder has a long history of use in beauty and healthcare [50,51]. In Japan, pearl extract has been widely used in cosmetics [52]. Although defective pearls have value, pearl farmers in Ago Bay prefer to produce high-quality pearls that can be sold at the highest price, which is challenging for them given that only approximately 20% of oysters are expected to produce saleable pearls, while approximately 5% will make top-quality gemstones [7,53].

3.3.2. Shell Waste

The results of this study suggested that the shell waste generated during pearl harvesting has significant environmental impacts, particularly in terms of solid-waste generation. Oyster shells are considered the largest and most visible waste generated by PF. For instance, harvesting 1 kg of pearls can generate approximately 15 kg of shell waste, which means that 600 kg of shell waste can potentially be produced during one cycle of pearl harvesting. To date, there are no facilities in the Mie Prefecture that can handle shell waste. Thus, pearl farmers in Ago Bay face challenges in terms of how they dispose of shell waste. Examples of the current efforts of pearl farmers regarding the handling of shell waste include exporting oyster shells to China (Figure 5a) and mixing oyster shells during road construction (Figure 5b).

Figure 5. (**a**) Akoya shell packaging used in exporting shell waste to China. (**b**) Oyster shells embedded in roads. These photos were taken by the first author in Ago Bay, Ise-Shima National Park, Mie Prefecture, Japan.

With limited available recycling processes for oyster shells, there is an opportunity for pearl farmers in Ago Bay to handle shell waste more sustainably. For example, oyster shells are a valuable source of calcium carbonate (approximately 80–90%), which can be used as a raw material for other products [54] and for various other applications, including agriculture and construction [55]. Analysis at the chemical and microstructural levels has revealed that oyster shells mainly consist of calcium carbonate, with few impurities [56]. There are also studies that have documented the usefulness of oyster shell waste in wastewater treatment, such as that by Lou et al. [57]. They found that oyster shells could be an effective and low-cost active filler for treating combined wastewater in estuaries. By exploring other options, such as recycling or repurposing oyster shells, we can create new economic opportunities, promote sustainable economic growth [55], potentially reduce environmental impacts, and create new opportunities for sustainable products [58].

3.3.3. Plastic Waste

The interviews documented that, on one pearl farm, approximately 9500 pieces of equipment were made from plastic materials. For example, plastic materials have been used to construct oyster cages and baskets. These cages are often made of plastic mesh or netting, which allows water to flow while keeping the oysters contained and protected from predators, allowing them to grow [59]. Furthermore, plastic materials are also used in other aspects of PF, such as the construction of rafts or platforms to suspend oyster cages in water. These structures can be made of plastic or other materials and are designed to provide a stable and secure environment for oyster growth and development [60].

Given that a pearl farm in Ago Bay can last more than 25 years, the accumulation of plastic waste that eventually disintegrates could be harmful to the PF industry. Currently, there are no recycling facilities or particular treatment facilities for broken equipment; thus, abandoned equipment can accumulate, potentially leading to long-term environmental impacts. For example, structures and tools made from plastic materials can be broken down into smaller pieces, ultimately leading to the buildup of microplastics that oysters and other filter feeders could ingest [61,62]. Plastic gear used in PF can also release significant amounts of hazardous chemicals or leach plastic over its lifetime, putting more pressure on pearl quality and environmental quality [63]. Therefore, efforts to reduce plastic pollution in PF are required. These include using alternative materials to construct infrastructure, such as biodegradable or natural materials that are less harmful to the environment, and implementing sustainable practices that can reduce plastic waste generation. Notably, a well-managed pearl farm requires few material replacements (less plastic), while the heightened awareness of pearl farmers in terms of environmental impacts reduces the associated risks [12].

4. Conclusions

An LCA of PF was conducted here to evaluate its environmental impacts in Ago Bay, Ise-Shima National Park, Japan. This study makes three major contributions to the literature. First, we have contributed to the scientific community by (a) performing an LCA of PF, which has not yet been conducted at this study site, and (b) adding concrete findings to the LCA of PF in the context of jewelry production, which is generally lacking in the literature. Second, we quantified the GWP of 1 kg of pearls produced and highlighted that PF has low GHG emissions when compared to other common jewelry production processes. Last, we have provided insights into how waste, from defective pearls to plastic waste, is handled in PF. Our study, although presenting limited results, highlights the importance of conducting an LCA in jewelry production to achieve a more sustainable path.

The main limitation of this study was that the LCIA was conducted on a limited number of pearl farms. Therefore, the key findings presented herein may not be representative of the entire PF industry. However, the lack of an LCA of PF in the scientific literature indicates that our study could be a starting point for conducting a more comprehensive LCIA of PF in Ago Bay, Japan. Considering the system boundary presented in Figure 2, our analysis was limited to GWP. Other environmental impacts that are relevant to PF practices, such as eutrophication, water pollution and depletion, and the introduction of invasive species [12,17,31,33], were excluded due to a lack of reliable data. Thus, there is an opportunity for future research to conduct an LCIA focusing on these environmental impacts.

There are also opportunities to implement circular-economy principles in the PF industry, such as recycling and reusing pearl components or developing innovative business models that extend the lifespan of pearls. Moreover, policy evaluation, such as assessing the effectiveness of policy interventions to promote sustainable pearl production and consumption, can also be conducted to advance the sustainability of PF. This could be in the form of evaluating the impact of financial incentives, certification programs, and consumer-awareness campaigns regarding adopting sustainable practices in the industry. By conducting further research in these areas, policymakers can gain deeper insights into pearl production's environmental, social, and economic dimensions. Although we did not analyze the interview results, our study revealed the importance of PF to communities in Ago Bay, Ise-Shima National Park, Japan, in terms of livelihood sources, which was also previously noted by Oe and Yamaoka [23]. The social and economic aspects of PF, including the well-being of pearl farmers and workers, local community development, and the economic benefits derived from sustainable pearl production, can be explored to advance further the understanding of the sustainability of pearls and enhance policy decisions. Therefore, future studies could also conduct a social life-cycle assessment that can capture the relationship between a piece of jewelry and local communities [64]. This knowledge can inform evidence-based policymaking and guide the development of strategies that promote sustainability and responsible practices throughout the entire life cycle of pearls.

Based on the results, we recommend that policymakers consider the following policy actions: encourage the jewelry industry to use sustainable materials; employ tax rebates, subsidies, or other financing sources to promote the adoption of eco-friendly commodities, such as pearls; and work with industry stakeholders to create standards and best practices for sustainable pearl sourcing and production. Given pearl production's low carbon footprint, jewelry makers may be inspired to switch to other eco-friendly materials. From the consumer's perspectives, legislative actions should consider increasing consumer knowledge and education regarding the effects of jewelry purchases on the environment. This could be done through, for instance, public-awareness campaigns to emphasize the benefits of pearls and other environmentally friendly materials from a sustainability standpoint. It is crucial to implement labeling programs or eco-certifications to assist consumers in making educated decisions. Sustainable practices in the pearl industry can be ensured by creating and implementing certification programs and standards, including recycling facilities for pearl production, and working closely with industry associations, environmental organizations, and other interested parties to build rigorous environmental effects, social responsibility, and ethical-practice standards. These criteria could increase customer confidence and enable them to make wise purchasing decisions, increasing the market for sustainable pearls.

Collaboration between academia, industry experts, and government bodies can facilitate knowledge exchange, technological advancements, and the adoption of sustainable practices. Innovative ways of reducing energy use, minimizing waste generation, and enhancing resource efficiency are also being explored. Although we acknowledge that uncertainty analysis is highly encouraged when defining life-cycle inventories for aquaculture because practices vary among farms [17], we did not perform such an analysis because our study was restricted to a limited number of pearl farms. However, incorporating uncertainty analysis into future studies will produce a better assessment of the accuracy of life-cycle inventories and LCA calculations [17].

In general, PF exhibits a low GWP while providing substantial socioeconomic benefits to the local community [23]. In terms of waste production, defective pearls can be used as an important source of cosmetics in Japan, whereas shell waste can be exported to China. Both practices could generate additional income for pearl farmers. Efforts to reduce plastic use in PF are ongoing. The discussions presented here can be used to inform the PF industry and stakeholders in Ago Bay about more climate-change-resilient PF techniques. This is relatively important given that producing high-quality pearls generates high financial returns [29]. As PF is an important economic and cultural asset of the bay, this study helps identify its impacts, which can be used to propose suggestions and/or develop frameworks to maintain the sustainability of the PF industry in Japan—the largest exporter of pearls globally.

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Data Availability Statement: The data used are presented in the study.

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