Turk. J. Fish.& Aquat. Sci. 24(9), TRJFAS23908
https://doi.org/10.4194/TRJFAS23908

Turkish Journal of FISHERIES and AQUATIC SCIENCES

RESEARCH PAPER

Towards Sustainable Shrimp Farming: Life Cycle Assessment of Farming Practices at the Less Favorable Areas of Yogyakarta's Southern Coast

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How to Cite

Tamariska, A.Y., Priyono, S.B., Suadi, S., Triyatmo, B. (2024). Towards Sustainable Shrimp Farming: Life Cycle Assessment of Farming Practices at the Less Favorable Areas of Yogyakarta's Southern Coast. *Turkish Journal of Fisheries and Aquatic Sciences*, *24(9), TRJFAS23908.* https://doi.org/10.4194/TRJFAS23908

Article History
Received 07 May 2023
Accepted 11 June 2024
First Online 26 June 2024

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Keywords
Aquaculture
Environmental impact
Life cycle assessment
Shrimp farming
Whiteleg shrimp

Abstract

The objectives of this study were to assess the potential environmental impacts that could be utilized to describe the current state of shrimp farming and propose alternative strategies for its management. Life Cycle Assessment (LCA) was held based on stages goal and scope, life cycle inventory, life cycle impact assessment, and interpretation by using SimaPro v.9.3.0.3 software and CML IA baseline V3.07 impact assessment method. The findings of this study demonstrated that super intensive shrimp farming had a lower potential environmental impact than intensive farming. The study indicated that super intensive shrimp farming produces a lower abiotic depletion potential (ADP), global warming potential (GWP), marine aquatic ecotoxicity potential (MTP), acidification potential (AP), and eutrophication potential (EP) than intensive farming. Potential environmental impact can be minimized by choosing a more environmentally friendly source of electrical energy and pond lining material and increasing the efficiency of the use of electricity and feed.

Introduction

Shrimp farming has grown rapidly in the last 30 years. Whiteleg shrimp *Litopenaeus vannamei* (Boone, 1931) accounts for almost 75% of the world's cultured shrimp production due to its good breeding ability, ability to be stocked from small post-larvae size, fast growth, uniform size, low protein requirements, and adaptability to changing conditions and various environmental conditions (Jory, 2019). Indonesia produced 708,660 tons of whiteleg shrimp in 2018, or 14.27% of the world's 4,966,200 tons (FAO, 2020, 2021b). This makes Indonesia the world's top shrimp producer after Brazil, China, Ecuador, India, Thailand, and Vietnam (Wati et al., 2013). Currently whiteleg shrimp farming has become a priority in Indonesia's aquaculture development (KKP, 2021). Shrimp production centres have emerged, including the Special Region of Yogyakarta (DIY), which produced 3,364 ton in 2015 (KKP, 2016). Shrimp farming has grown rapidly in DIY and other areas of Java's southern coast, converting the less favorable areas in the form of sandy soils into shrimp ponds (Suadi et al., 2019). Shrimp farming in sandy coastal areas is possible using biocrete technology or polyethylene plastic as pond liner (Priyono, 2020). Shrimp farming development is achieved through intensification by increasing a stocking density, improvement of feed management, and application of aeration, water exchange, biosecurity, disinfection, and probiotics (FAO, 2016). Higher stocking density boosts productivity.

Shrimp farming provides food, jobs, regional income, and export trade (Klinger & Naylor, 2012; Phillips et al., 2016; Suadi et al., 2019). However, simultaneously shrimp farming also has a negative impact, especially on the environment. Shrimp farming requires land, water, feed, energy, medicines, and chemicals, which has increased natural resource exploitation and environmental emissions (Fitwi et al., 2012). Numerous studies have noted the negative externalities of uncontrolled and rapid growth of the shrimp industry's in various parts of the world, including the use of large amounts of energy and resources; loss of biodiversity; water pollution due to increasing level of nutrients, chlorophyll-a and dissolved organic matter; mangrove deforestation and eutrophication; and encourage the spread of harmful pathogens and diseases (Abdullah et al., 2019; Bull et al., 2021; Cao, 2012; Lacerda et al., 2021; Macusi et al., 2022). More intensive shrimp farming systems require more complex management, resulting in a higher potential environmental impact (Cao, 2012). However, growth in global shrimp consumption demands a shift to more intensive shrimp farming system, so ways are needed to minimize its potential environmental impacts.

Evaluation of sustainability in shrimp farming is needed to determine the potential environmental impacts arising from shrimp farming activities. Life Cycle Assessment (LCA) is a tool to evaluate the sustainability of aquaculture with a normative and standard approach (Lazard et al., 2014). The implementation of LCA can aid in the development of sustainable shrimp farming strategies by identifying potential environmental impacts. The objectives of this study were to assess the potential environmental impacts that could be utilized to describe the current state of shrimp farming and propose alternative strategies for its management.

Material and Method

Research Design

Life Cycle Assessment (LCA) was conducted in intensive farm located at Kuwaru Beach, Bantul Regency, DIY, Indonesia and super intensive farm located at Trisik Beach, Kulon Progo Regency, DIY, Indonesia (Figure 1). LCA was held based on guidelines ISO 14040:2006 including the stages of goal and scope definition, inventory analysis, impact assessment, and interpretation. The research object was determined based on the criteria for shrimp farms that have complete production records. The current study is focused on the commercial scale of intensive and super intensive shrimp farming with liner technology in less favorable areas.

The scope of this research is cradle to gate, including resource extraction until the shrimp is harvested from the farm (Figure 2). Functional unit one-ton fresh shrimp is applied. Secondary data based on Cao (2012) is used in the calculation of larvae and shrimp feed production.

Life Cycle Inventory

The data consists of primary and secondary data. Primary data was obtained directly from farm production records. Primary data was taken including infrastructure, material requirements for shrimp operation, energy use, and transport. The use of infrastructure components was calculated for ten years of service life. Material requirements for one-ton shrimp production are shown in Table 1.

Both farms used ground water for farming. Both farms show different material requirements on infrastructure, operational, and energy. Intensive farm uses 46.58% more pond lining material. This is due to the difference of material that affects thickness and final mass of pond lining. On operational, intensive farm shows more variation and numerous components to maintain water quality. This is due to intensive farm applied a less water exchange system compared to super intensive farm. Super intensive farm shows higher larvae and feed requirements because of higher stocking density. On energy, intensive farm used 84.39% more electricity energy and caused higher use of diesel fuel for generator to cover higher electricity usage.

The calculation of the transport component in feed production is shown in Table 2. There are raw materials for feed production obtained from import and domestic which are calculated based on Henriksson et al. (2017). Wheat flour and soybean flour are entirely imported. Fish meal and maize flour are partly obtained from domestic (Banyuwangi Regency, Indonesia and Cilegon Regency, Indonesia). Transport of imported materials is calculated using cargo ship from port origin to Tanjung Priok Port, Indonesia, followed by trucks to feed factory. Transport of domestic materials is calculated using trucks from the regency of origin to the feed factory. The feed factory of intensive farm located on Gresik Regency, Indonesia and super intensive farm located on Serang Regency, Indonesia. The use of electricity in both farming systems is shown in Table 3.

Differences in farming systems also show differences in the amount of electrical energy required by each component. The higher use of electricity in the intensive system is caused by the operation of the paddle wheels which are turned on entirely for 24 hours throughout the cycle, in contrast to the super intensive system which turns on the paddle wheel gradually (according to the day of culture) so that it uses less electricity.

Impact Assessment

The potential environmental impacts associated with this study were calculated using SimaPro v.9.3.0.3 with CML IA baseline V3.07 impact assessment method.

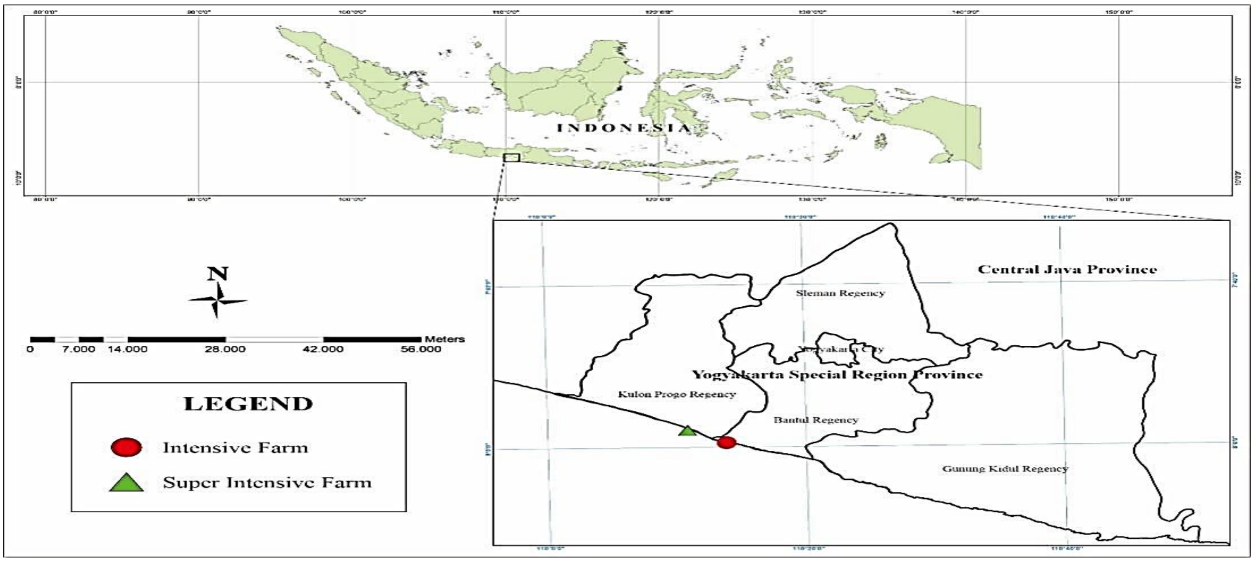

Figure 1. Location of intensive and super intensive shrimp farm

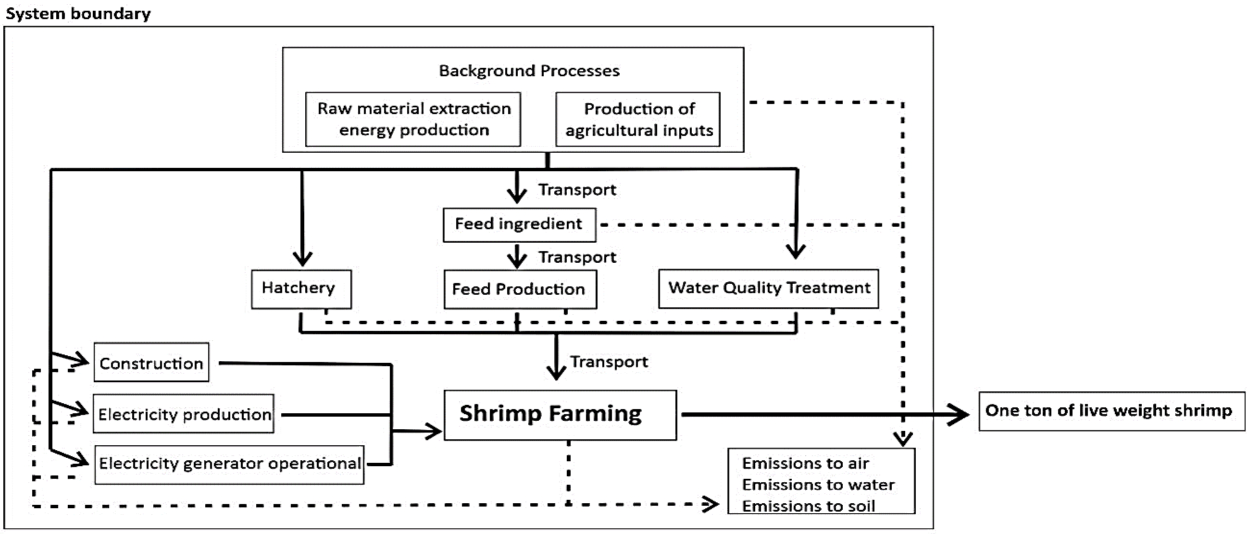

Figure 2 System boundary of LCA

Table 1. Material requirements for one-ton shrimp production

	Material	Intensive	Super Intensive
Infrastructure	Pond liner (kg)	664.94*	355.21**
	PVC pipe (kg)	56.70	54.03
Operational	Larvae	96.337	196,779
	Feed (kg)	1,553.53	2,643.10
	Molasses (kg)	21.85	14.13
	Dolomite (kg)	97.41	-
	Calcium carbonate (kg)	-	18.19
	Rice bran (kg)	82.68	-
	Hydrogen peroxide (kg)	9.97	-
	Copper sulfide (kg)	0.91	-
	Chlorine (kg)	17.45	-
	Benzal Chloride (kg)	-	0.83
	ZA fertilizer (kg)	28.30	-
	Sodium bicarbonate (kg)	-	87.32
	Yeast (kg)	0.342	1.202
Energy	Electricity (kWh)	9,992.58	5,412.40
	Diesel fuel for generator (litre)	39.92	7.86

*: intensive farm used high density polyethylene (HDPE)

**: super intensive farm used low density polyethylene (LDPE)

Table 2. Transport components in the calculation in feed production

Component	Source and Proportion		Distance (m)		
			Import*	Domestic	
	Import	Domestic		Intensive	Super Intensive
Fish meal	Peru (78%)	Banyuwangi (22%)	26,248,000	1,100,000	315,000
Wheat flour	Australia (100%)	-	3,366,000	-	-
Maize flour	India (18.24%)	Cilegon (81.76%)	5,687,000	58,000	902,000
Soybean flour	US (100%)	-	25,146,000	-	-

Table 3. The use of electricity to produce 1 ton of shrimp

Component	Intensive		Super Intensive	
	Amount (kWh)	Percentage (%)	Amount (kWh)	Percentage (%)
Paddle wheel	7,320.50	67.21%	939.60	17.26%
Water pump	3,570.15	32.78%	4,393.52	80.72%
Illumination	1.43	0.01%	109.87	2.02%
Total	10,892.08	100%	5,442.99	100%

Results

The Performance of Intensive and Super Intensive Shrimp Farming

The profile and performance of intensive and super intensive are shown in Table 4. Classification of intensive and super intensive shrimp farming was developed based on Jory (2019). Stocking density of 26-120 shrimp/m^2 classified as intensive and 120-500 shrimp/m^2 as super intensive. Intensive farm shows higher land use and gives higher production per pond, while super intensive farm shows higher stocking density. Super intensive farm gives better result on productivity, final shrimp size, ABW, and ADG. Super intensive farm also shows a less land use.

The study considers the following potential environmental impacts: Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Marine Aquatic Ecotoxicity (MTP), Acidification Potential (AP), and Eutrophication Potential (EP). The impact assessment of one-ton shrimp production is shown in Table 5 and their proportions in Figure 3.

Intensive farm shows a higher potential for environmental impact in all categories, in the ADP higher 11.21%; GWP higher 52.22%; MTP higher 73.70%; AP higher 42.11%; and EP higher 65.13% compared to the super intensive system. The main components that contribute to potential environmental impacts are the use of electricity, feed, and pond lining material (Figure 4).

The main contributors of ADP are the use of high density polyethylene (HDPE) pond liner and electricity. HDPE is derived from petroleum and to produce 1 kg of HDPE needed 1.75 kg of petroleum in the form of energy and raw material (Kumar et al., 2011). Coal contributed 76.22% power plant in Indonesia (Sunaryo et al., 2020) which was reported as the cause of GWP, MTP, AP, and EP (Shindell & Faluvegi, 2010). Coal can become a potential source of MTP in water due to their leaching. The contain of mercury (Hg) and lead (Pb) are elements lethal to organisms, arsenic (As) is potentially mutagenic, As and Pb are both carcinogenic (Tretyakova et al., 2021). The content of polycyclic aromatic hydrocarbons (PAHs) is also known to have toxic impact on bone metabolism, liver metabolism, and reproduction in fish (Honda & Suzuki, 2020). The main contributor of AP mainly caused by human activities from burning fossil fuels thus producing sulfur dioxide (SO_2) and nitrous oxide (N_2O) which react with rainwater causing acid rain (Patel, 2021). The main contributor of EP caused by the presence of nitrate (NO_3^-) in coal (Dunmade et al., 2019).

Atmospheric deposition (AD) process is associated with AP, and EP. AD process refers to United States Department of Agriculture (USDA, n.d.). AD process started with the burning of coal which produce SO_2 and N_2O. Both materials oxidized by ozone (O_3) and reacted with ammonia (NH_3) thus producing ammonium (NH_4^+), NO_3^-, and sulphate (SO_4^{-2}). NH_4^+ and NO_3^- contributed to EP. SO_4^{-2} reacted with H^+ ions to produce sulfuric acid (H_2SO_4), which drives the acid rain and contributes to AP.

The result of potential environmental impact has been shown in the impact assessment. Electrical and feed components are also known to be the main contributors to the potential environmental impact in shrimp farming (Cao, 2012; Mu'in et al., 2013; Muñoz et al., 2021). A sensitivity analysis assessed impact assessment methodology congruence. This analysis rigorously verifies the significance and practicality of sensitivity analysis data in drawing conclusions and recommendations (ISO, 2006). Table 6 shows the analytical process, which evaluated various methods. These comparisons are needed to assess potential environmental impacts because different methods may yield different results (Mu'in et al., 2013).

The most significant disparity in potential environmental impact is observed in the range of 8.60-

Table 4. Intensive and super intensive shrimp farms profile and production performance

Indicator	Intensive Farm (n=14)	Super Intensive Farm (n=6)
Area (m^2)	3,021 ± 769	820 ± 225
Density (shrimp/m^2)	120 ± 10.72	229 ± 32
PL size (day)	8	8
Day of culture (day)	84 ± 15.83	104 ± 21
Survival rate/SR (%)	70.93 ± 19.49	42.71 ± 14.17
Feed conversion ratio/FCR	1.65 ± 0.29	2.89 ± 0.50
Production per pond (kg)	3,758 ± 2,172	953 ± 239
Productivity (kg/m^2)	1.065 ± 0.493	1.393 ± 0.013
Final shrimp size (shrimp/kg)	74 ± 34	62 ± 21
Average body weight/ABW (kg)	0.0135 ± 0.0043	0.0179 ± 0.0051
Average daily growth/ADG (kg/day)	0.000161 ± 3.1E-5	0.000173 ± 4.0E-5

Table 5. Impact assessment of one-ton shrimp production

Component	ADP (kg Sb eq)		GWP (kg CO_2 eq)		MTP (kg 1,4 DB eq)		AP (kg SO_2 eq)		EP (kg PO_4 eq)	
	I	SI	I	SI	I	SI	I	SI	I	SI
Construction	0.009049	0.004928	1,708.00	1,047.00	9.68.E+05	6.72.E+05	6.17	3.95	1.38	0.96
Larvae	0.000040	0.000081	31.60	64.50	6.57.E+04	1.34.E+05	0.18	0.37	0.19	0.38
Feed	0.002790	0.004720	1,820.00	3,060.00	3.12.E+05	5.26.E+05	11.60	19.40	3.68	6.19
Water Quality Treatment	0.005153	0.004447	163.19	127.35	2.61.E+05	2.35.E+05	1.45	1.16	0.54	0.33
Electricity	0.003690	0.004810	11,100.00	6,110.00	2.66.E+07	1.47.E+07	47.00	25.90	66.10	36.30
Generator	0.000777	0.000378	1,401.10	694.22	2.47.E+05	1.20.E+05	6.24	3.05	1.41	0.70
Transport	0.000058	0.000019	1,404.91	477.93	2.34.E+04	7.98.E+03	7.51	2.56	1.77	0.60
Total	0.021556	0.019383	17,628.80	11,581.00	2.85.E+07	1.64.E+07	80.15	56.40	75.06	45.45

*I: intensive, SI: super intensive

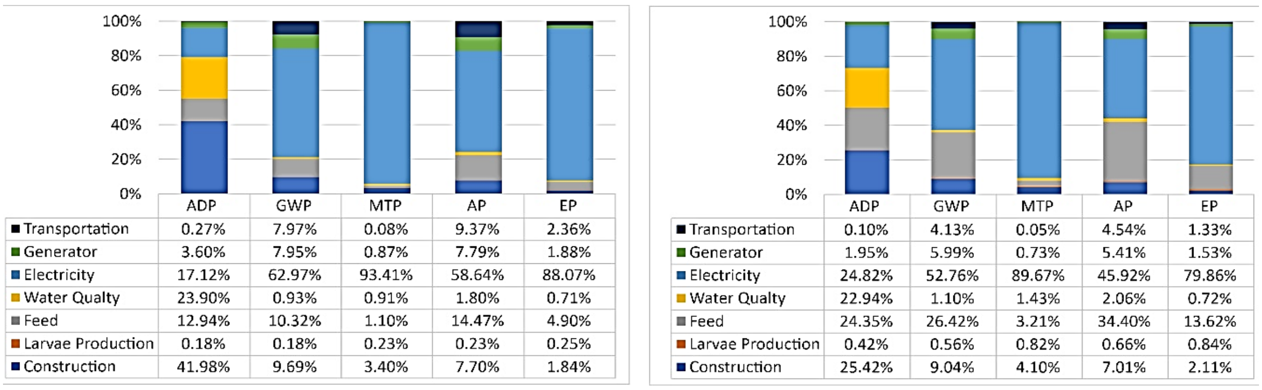

Figure 3. Proportion of one ton shrimp production (A: intensive, B: super intensive)

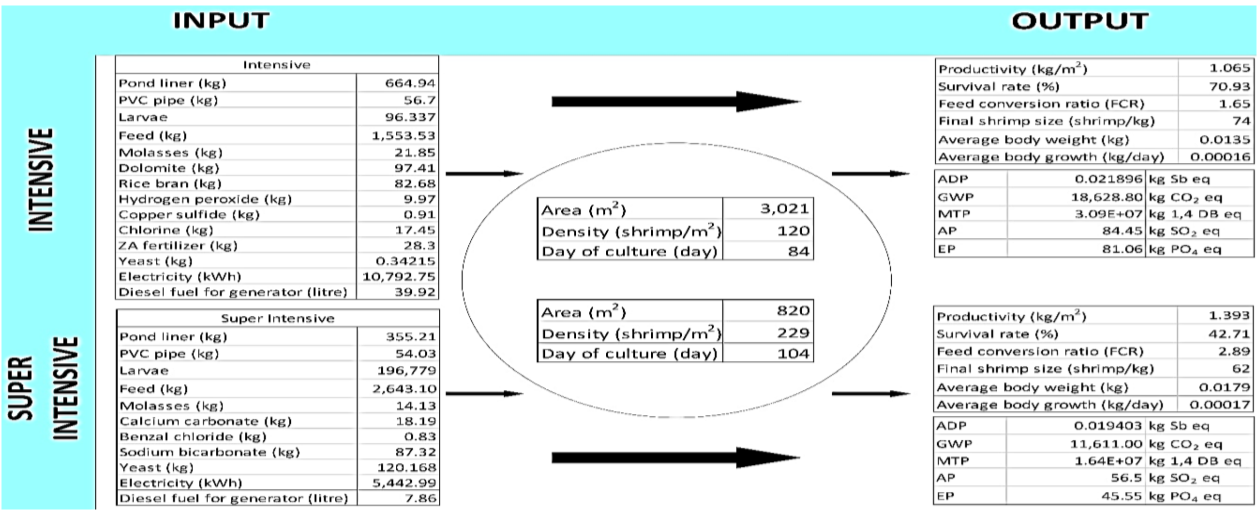

Figure 4. The whole result of this research

Table 6. Comparison the results with other impact assessment methods.

Method	Intensive			Super Intensive		
	GWP	AP	EP	GWP	AP	EP
CML IA baseline V3.07*	17,700.00	80.2	75.1	11,600.00	56.4	45.4
EPD 2018 V1.03	17,700.00	87.7	75.1	11,600.00	61.8	45.4
TRACI 2.1 V1.06	17,600.00	87.3	-	11,600.00	61.6	-
Eco Indicator 95 V2.06	17,300.00	87.1	74.8	11,300.00	61.5	45.1

*: used on this research

9.35% in intensive farm and 9.04-9.57% in super intensive farm. Because the software program calculates in a closed system, variations in the impact assessment method may result in different outcomes (Iswara et al., 2020).

Discussion

This research presents a comparative analysis of the potential environmental impacts associated with intensive and super-intensive shrimp farming systems. It concludes that super-intensive farm generally has a lower potential environmental impact than intensive farm, primarily due to more efficient electrical energy use, environmentally friendly pond lining materials, and closer proximity to production material suppliers, reducing transportation needs. Nevertheless, the potential environmental impact of super-intensive farm may be greater when specific factors are omitted from the Life Cycle Assessment (LCA). This is primarily due to the fact that intensive farm employs a more extensive range of water quality treatment materials and necessitate greater maintenance as a result of less frequent water changes. Overall, the study, supported by findings from Belettini et al. (2018) and Cao (2012), indicates that the advanced technology and efficient management practices in super-intensive farming, such as the use of liners and paddle wheels, lead to its reduced potential environmental footprint compared to intensive farming systems. The result shows super-intensive farm can have a lower impact than intensive. This is in line with the concept of sustainable intensification of aquaculture (SIA) which mainly focused on improving production and efficiency of resource used (land, water, feed, and energy) simultaneously with minimizing environmental impact (FAO, 2016).

Improvement Recommendation

Shrimp farming can be more sustainable by using a more environmentally friendly source of electrical energy, using more efficient electricity and feed, and selecting a more environmentally friendly pond lining material. Indonesia's coal-based electricity has a high potential environmental impact. Scenario is prepared by comparing the potential environmental impacts of available sources of electrical energy in Indonesia (Figure 5).

Intensive farm use more electricity, increasing their potential environmental impact. The value of ADP shows small differences than other electricity sources because renewable energy sources require a lot of material during production but less during operation (Raugei et al., 2020). In both farms' scenarios, wind energy has the greatest potential environmental impact on ADP. Wind power plants need heavy metals, especially copper (Cu), aluminium (Al), and nickel (Ni), which increase on ADP value (Raugei et al., 2020). GWP, MTP, AP, and EP are most affected by coal-generated electricity. Hydropower can replace coal and has a lower potential environmental impact.

Intensive farm used 84.39% more electricity than super intensive, which is mainly due to 66.62% more electricity consumption for paddle wheel on intensive farm. BSN (2014) states that the number of paddle wheels meets Indonesia National Standard (SNI) 8007:2014, but the operational duration is unregulated. Since intensive farm runs paddle wheels 24/7 from the first day of culture to harvest, they use lots of electricity. Super intensive farm used more paddle wheels as shrimp age increases and less during the day to save electricity. Both farms have different paddle wheel-to-production ratios. One HP paddle wheel can cover 260 kg of shrimp in super intensive farm and 252 kg in intensive farm. Since paddle wheels use the most electricity, standardizing their operating duration and ideal coverage can boost efficiency. The number of wheels can be modulated based on the age of the shrimp, allowing for partial activation of the paddle wheels, as the larvae are kept until they are ready for harvest. Implementing a reduction in the number of paddle wheels during daylight hours is also possible. Enhancing electrical energy efficiency promotes the sustainable intensification of aquaculture (FAO, 2016). Food conversion ratio (FCR) measures feed efficiency. Scenarios were carried out by compiling FCR changes to 1.50 (referred to ideal value based on SNI 8008:2014) and 1.25 (Figure 6).

FCR values affect all potential environmental impacts. The higher feed demand makes super intensive farm more potentially to cause environmental damage. More efficient feeding reduces water pollution and overfishing (Rubel et al., 2019). Recommendation is given to maintain feed efficiency to minimize potential environmental impacts.

Both farms use different pond lining materials. Super intensive farm used 80-micron Low Density

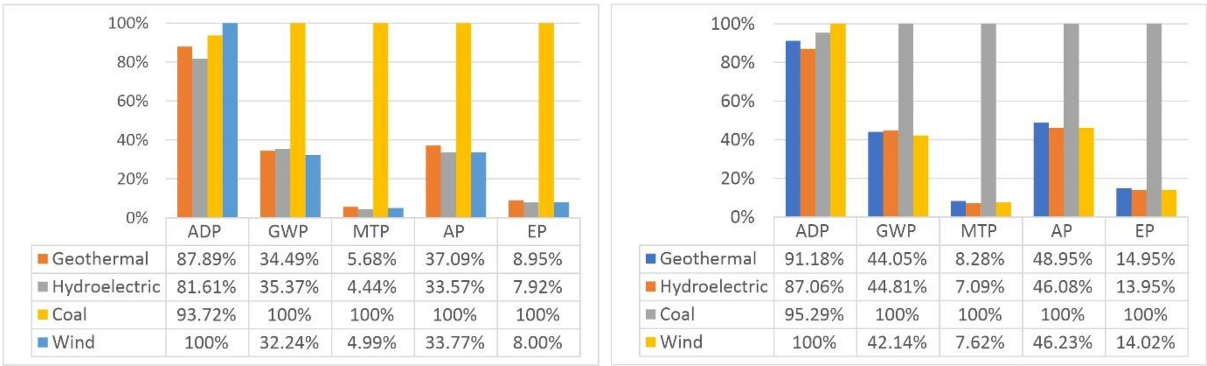

Figure 5. Scenario of substitution of electrical energy sources (A: intensive, B: super intensive)

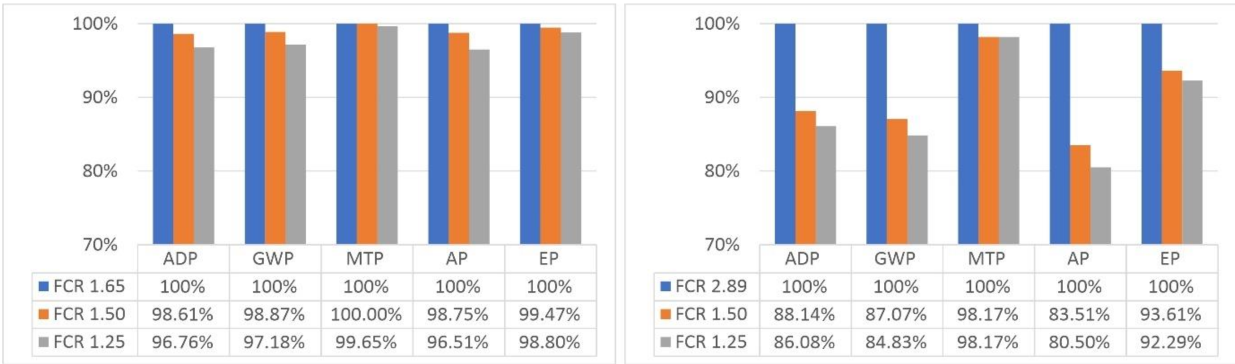

Figure 6. Scenario changes in FCR values (A: intensive, B: super intensive)

Polyethylene (LDPE) pond liners, while intensive farm used 800-micron HDPE. Pond liners vary in type and thickness, affecting mass. Intensive farm used 46.58% more pond lining. Figure 7 shows 10-year HDPE and LDPE pond lining scenarios in the same area. HDPE lasts 10 years, requiring one installation, while LDPE lasts two years, requiring five times. The potential environmental impact of HDPE was higher. Pond lining with LDPE reduces potential environmental impact.

The current study focuses on commercial scale of intensive and super intensive shrimp farming with liner technology in less favorable areas. However, it is recommended to include more innovative aspects of evaluation and comparison in future research. The future research might include topics such as evaluating the gene expression of organisms involved and susceptibility to diseases depending on the culture systems involved; and comparison between production system such as the application of biofloc or probiotics in crop water recirculation systems to obtain more comprehensive results.

Conclusion

The study found that intensive shrimp farming results in an 11.21% higher in abiotic depletion potential (ADP), a 52.22% higher in global warming potential (GWP), a 73.70% higher in marine aquatic ecotoxicity potential (MTP), a 42.11% higher in acidification potential (AP), and a 65.13% higher in eutrophication potential (EP) compared to super intensive farming. Thus, the implementation of a super intensive farming system has the potential to result in a reduced potential environmental impact and serve as evidence that shrimp farming might be advanced towards a super intensive level. Farm managers thus need to exercise

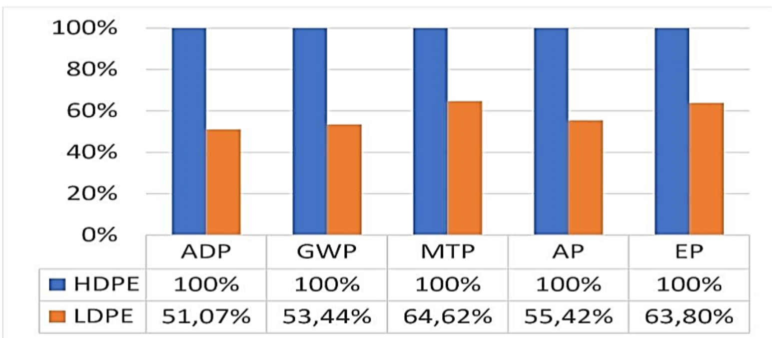

Figure 7. Comparison of the potential environmental impacts from HDPE and LDPE pond lining material

prudent management practices when it comes to the choice of pond lining materials, efficient electricity usage, and implementing effective feed management strategies to reduce environmental impact of shrimp farming.

Ethical Statement

All subjects gave consent before they participated in this research that the information provided about shrimp farming would be used in this research.

Funding Information

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contribution

First Author: Conceptualization, Data Curation, Investigation, Methodology, Formal Analysis, Visualization and Writing -original draft, Project Administration; Second Author: Conceptualization, Methodology, Formal Analysis, Writing -review and editing, Supervision; Third Author: Conceptualization, Methodology, Writing -review and editing, Supervision; Fourth Author: Writing -review and editing.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was conducted as a part of M.Sc. studies in Fisheries Science in Department of Fisheries, Faculty of Agriculture, Universitas Gadjah Mada, which also funded the project. The authors would like to express their gratitude to the owner of shrimp farms for clear and concise data provision for this research.

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