

Assessing the Environmental Footprint of Rice-Prawn Co-culture Systems: A Life Cycle Approach to Sustainable Farming



Note. “Siem Reap Rice Fields” by N.D. Strupler, 2012, photograph, Flickr, (<https://www.flickr.com/photos/strupler/page61>). CC-BY-2.0

Aline Mellersh

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MSc. Industrial Ecology

Leiden: s44929109

TU Delft: s6348718

1st Supervisor: Patrik Henriksson

2nd Supervisor: Linda Kamp



Universiteit
Leiden



Executive summary

Rice is a staple source of food for approximately three billion people worldwide, forming the backbone of food security in many developing nations (Lansing & Kramer, 2011). However, conventional rice production carries substantial environmental costs. Flooded paddies are the world's largest agricultural source of methane, a greenhouse gas (GHG) roughly 25 times more potent than carbon dioxide (Forster et al., 2007). Moreover, paddy fields frequently suffer from the overuse of fertilisers and pesticides which degrades soils and waterways, and negatively impacts biodiversity (Forster et al., 2007; Lansing & Kramer, 2011). Integrated systems, such as rice-fish or rice-prawn (RP) co-cultures, offer a promising approach to reduce environmental pressures while maintaining productivity. In Cambodia, RP farming is increasingly practiced, but its environmental performance has not been quantified, leaving policymakers and farmers without evidence to guide sustainable expansion.

This MSc thesis, conducted under the discipline of Industrial Ecology, investigates the environmental impacts of RP co-culture systems in Cambodia using a Life Cycle Assessment (LCA) approach. RP co-cultures represent complex socio-ecological systems, where flows of nutrients, energy, and emissions interact across the farm ecosystem. LCA allows for quantification of these interactions across the entire production chain, and scales them to a common unit of reference (functional unit), identifying trade-offs and environmental hotspots while informing strategies for sustainable intensification. While prior LCA studies have explored rice-animal systems, predominantly showing clear improvements in environmental sustainability, there is a significant research gap for RP systems in Cambodia (Wang et al., 2024). This thesis addresses that gap by collecting primary data from local farms; mapping inputs, outputs, and management practices over one agricultural season; and conducting a full LCA to quantify environmental impacts.

The results showed that RP co-cultures exhibited higher environmental burden. Field-level farming operations, manure production, and diesel combustion were identified as the primary life cycle hotspots across both systems. However, when assessed per unit of economic or nutritional output, monoculture experienced higher environmental impacts for Climate Change, Land Use, and Water Use. Indeed, despite their lower productivity, RP systems produced substantially less methane per unit of output than monoculture, a meaningful climate advantage obscured by aggregated impact scores. As RP farming continues to develop in Cambodia, if co-cultures want to show genuine potential to simultaneously support smallholder livelihoods, reduce methane emissions from rice cultivation, and contribute to more sustainable food production, targeted improvements to productivity and input management need to occur. Yet, this makes them a worthwhile focus for continued investment, research, and policy support.

Key words: Life Cycle Assessment, Co-cultures, Agro-aquaculture, Rice-animal, Sustainable Agriculture, Sustainable Food Security.

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Table of Abbreviations

Abbreviation	Description
ALCA	Attributional Life Cycle Assessment
CH ₄	Methane
CLCA	Consequential Life Cycle Assessment
CO ₂	Carbon Dioxide
EF	Environmental Footprint
EoL	End-of-Life
GHG	Greenhouse Gas
IC	Impact Category
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
MV	Market Value
N	Nitrogen
N ₂ O	Nitrous Oxide
NH ₃	Ammonia
NO ₃ ⁻	Nitrate
NPK	Nitrogen, phosphorus and potassium fertiliser
RA	Rice - Animal
RC	Rice - Crayfish
RF	Rice - Fish
RP	Rice - Prawn
SM	Supplementary Material
UP	Unit Process

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1.

Introduction

Global food systems are increasingly characterised by a growing paradox: to operate within planetary boundaries while adequately meeting global nutritional needs (Gordon et al., 2017; Willett et al., 2019). In order to address this, a systemic transformation is imperative to reduce environmental impacts, sustain livelihoods, and meet rising food demands (Ericksen et al., 2010; IPES-Food, 2016; Schipanski et al., 2016). Rice currently feeds around 3 billion people, dominating many agricultural landscapes, and represents a critical case study within this context (Lansing & Kramer, 2011). As populations and therefore demand continue to grow, the widespread reliance on rice is paired with a heavy environmental cost; yet it still lies at the centre of many national food security strategies (Lansing & Kramer, 2011). Additionally, the FAO's 2024 State of World Fisheries and Aquaculture report emphasised the important role global aquaculture is expected to play in addressing food insecurity. As both aquaculture and agriculture expand to meet growing demand, Cambodia, where aquatic food and rice have long been central to diets and livelihoods, will face a pivotal transition (FAO, 2024; Hartje et al., 2018).

Despite Cambodia's positive developments towards economic growth over the past few decades, it still faces serious food security challenges, which are only exacerbated by climate change (Cheang & Wong, 2014; Anyango et al., 2026). Methane (CH₄) makes up about 20% of the global GHGs and is 25 times more potent than carbon dioxide (CO₂) (Forster et al., 2007; Robin & Wassman, 2003). Flooded rice paddies represent the largest source of agricultural CH₄ emissions globally. Excess use of fertilisers and pesticides further intensify ecological pressures, degrading soils, waterways, and threatening biodiversity (Lansing & Kramer, 2011; Li et al., 2019). Similar issues arise for the aquaculture sector: historically productive capture fisheries have been declining in Cambodia due to overfishing and global warming (Chevalier et al., 2023; Joffre et al., 2021). These pressures challenge the long-term sustainability of conventional monoculture rice and aquaculture production and highlight the urgency of developing systems that can sustain food security and economic growth in a changing climate.

Integrated systems such as rice-fish (RF), rice-shrimp (RS) and rice-prawn (RP) co-cultures have long existed across Asia and beyond. RF farms have been documented in China for over 1700 years (Lu & Li, 2006) yet their adoption remains limited, in part due to a lack of robust, context-specific environmental assessments. In Cambodia, RP farming could represent a promising adaptation within this broader search for sustainable alternatives,

offering a way to maintain productivity while mitigating the climate and environmental impacts inherent to conventional rice agriculture (Freed et al., 2021). Somony Thay, Cambodia's Director of the Department of Aquaculture Development said that agricultural ecotransition, specifically rice-animal (RA) co-cultures, are vital for Cambodia's development. They argue that it effectively increases “productivity while minimizing environmental impacts, leading to improved food security and enhanced economic resilience[...] the integration diversifies income sources, making farmers less vulnerable to economic shocks affecting a single crop” (Xinhua, 2025). This makes Cambodia a particularly relevant context for assessing low-input, resilience-oriented farming systems before agricultural pathways become locked into more intensive models. While RP co-culture is increasingly being adopted in practice, the environmental performance remains poorly quantified (Pazmiño et al. 2025), leaving policymakers and farmers without the evidence needed to guide its sustainable expansion.

Evaluating the impact of RP co-cultures is directly linked to the academic discipline of Industrial Ecology as such co-culture systems represent complex coupled human-natural metabolic systems where resource flows, emissions, and ecological processes interact. Understanding these interactions through a Life Cycle Assessment (LCA) will allow low-impact food systems to be designed while also steering agricultural development toward strategies that reduce emissions, enhance resilience, and support livelihoods. LCA is particularly relevant for this study, as it enables a comprehensive evaluation of trade-offs across the entire production chain, and would provide a scientific underpinning of this practice for Cambodian rice-prawn farmers. By generating empirical data on Cambodian RP farming, this study fills a critical gap and supports a more scientifically grounded transition toward sustainable food production in the region.

Few LCA studies assess the environmental impacts of aquaculture within rice paddies. Wang and colleagues (2024) conducted a LCA finding that RF and rice-crayfish (RC) co-culture systems can produce substantial amounts of low-carbon protein and significantly reduce GHG emissions and land use, highlighting their potential to support sustainable diets and lower the environmental footprint of rice production. However, a research gap persists in LCA studies on prawn co-cultures geographically focussing on Cambodia.

2.

Literature Review

2.1. Farming Systems in Cambodia

From 1990, in the aftermath of the Khmer Rouge regime, Cambodia saw substantial socioeconomic progress, sparking rapid economic growth, and significant poverty reduction (Chheang & Wong, 2014; Diepart & Ngin, 2020; Olsson & Wohlgemuth, 2003). Today, agriculture stands as one of Cambodia's key economic pillars, contributing 22% of GDP in 2022 (FAO, 2023). The Cambodia Agriculture Survey (2020) estimated that 57% of all households in the country have agricultural holdings. Despite these advances, food security remains a persistent challenge, particularly in rural areas where over 70% of the population resides (CGIAR, 2024). Cambodia's rural landscape is closely linked to freshwater ecosystems, with traditional systems such as rice field fisheries sustaining livelihoods for centuries (Anyango, 2026). However, the widespread availability of wild fish from capture fisheries in the Tonle Sap floodplain and surrounding areas, particularly during the wet season, reduces market demand for farmed fish and poses a significant challenge to smallholder farmers.

Cambodia experiences a tropical monsoon climate, in which there is a rainy season (May to October) and a prolonged dry season. While 75% of Cambodia's rice is produced during the rainy season, it is grown throughout the year (Saito et al., 2025). At the same time, the dominance of rice in Cambodia's agricultural export market has encouraged farmers to intensify production through double or triple cropping, allocating large areas to rice cultivation. However, such farming approaches come with clear burdens.

The increasing pressures associated with food security, economic development, and environmental sustainability highlight the importance of a transition toward more productive and environmentally sustainable farming systems (FAO, 2022; Pretty, 2018). In Cambodia, aquatic foods account for more than half of animal protein intake (FAO, n.d.). This represents one of the highest rates globally, underscoring the importance of shifting to resilient and environmentally sustainable farming in Cambodia. In 2026 Cambodia formally recognised aquatic food systems as a national priority in the Second Roadmap for Food Systems for Sustainable Development 2025-2030. Of the six national "Game-Changing Actions", one is dedicated specifically to aquatic foods, marking the first time that aquaculture systems have been fully integrated into national food systems planning (Sao, 2026).

2.1.1. Barriers to Monoculture Farming

In Cambodia, decades of monoculture farming have contributed to land degradation and declining soil and water quality, increasing the reliance on external inputs to sustain yields. The over-fertilisation of rice with nitrogen (N) is a strong contributor to high emissions in which nitrous oxide (N₂O) is released (which is roughly 300 times more potent than CO₂ as a GHG) while also depleting stratospheric ozone (Lansing & Kramer, 2011). Eutrophication from nitrogen inputs, including both N₂O and Ammonia (NH₃), are also among the most serious anthropogenic threats to coastal waters worldwide (Li et al., 2019; Valiela et al., 1992; Vitousek et al., 1997). In aquaculture farms, high stocking densities, combined with intensive application of pelleted feed, can exacerbate nutrient loading, leading to eutrophication, hypoxia, and increased GHG emissions (Li et al., 2019).

Monoculture rice paddies are directly responsible for about half of all CH₄ emissions (Lansing & Kramer, 2011). Yet, effective mitigation strategies remain underexplored. In rice monoculture systems, two main mechanisms drive high emission rates: the flooding of paddies causes CH₄ emissions and the over-fertilisation with N causes N₂O emissions. When rice paddies are submerged, anaerobic conditions activate methanogenic bacteria that produce CH₄. The gas escapes to the atmosphere through three main pathways:

- 1) Diffusion: the passive movement of CH₄ from water to air, driven by concentration gradients;
- 2) Ebullition: in which gas bubbles rise from sediments;
- 3) Plant-mediated transport: where CH₄ travels through the aerenchyma tissues of rice stalks.

(Lansing & Kramer, 2011)

Understanding these pathways is critical for evaluating mitigation strategies in rice-based systems. In the face of such issues, organic monoculture farming could be turned to as a feasible strategy to decrease such GHG emissions, as it can help decrease N₂O emissions and reduce reliance on synthetic fertilisers (Bocean, 2025). However, organic rice fields have been linked to similar or even higher CH₄ emissions than non-organic rice fields, as they often incorporate compost, manure or crop residues as fertiliser (Song et al., 2025). Nevertheless, both organic and non-organic monoculture farmers face issues beyond GHG emissions. In rice farms, high input costs and volatile market prices are increasingly threatening smallholder profitability (Phichong et al., 2025). Similarly, for aquaculture farms, Dey et al. (2019) note that although historically lucrative, high feed costs have driven both small and larger-scale farmers to diversify toward alternating or co-culture systems.

2.2. Rice-Prawn Co-Cultures

Increasing pressures associated with food security, economic development, and environmental sustainability have accelerated interest in more productive and resilient farming systems (FAO, 2022; Pretty, 2018). RA co-cultures have been proposed as a viable pathway for reducing the GHG footprint of conventional rice systems while maintaining productivity (Freed et al., 2021; Xie et al., 2011; Ahmed & Garnett, 2011). In Cambodia specifically, RP farming is increasingly recognised for its market potential, reduced agrochemical reliance, and benefits to soil, water, and aquatic biodiversity, with the Department of Aquaculture Development actively promoting both RF and RP systems through collaborative development projects (Phichong et al., 2025).

Within the scope of my research, RA co-cultures are defined as intentional integrated farming systems in which rice is cultivated concurrently alongside other organisms (such as fish, shrimp, and/or prawns) within the same production unit. They often rely on ecological and mutualistic interactions to enhance productivity, reduce dependence on external inputs and diversify income (Xie et al., 2011; Lansing & Kramer, 2011; Anyango, 2026). Polycultures (systems involving more than two species) fall outside this scope (Misra & Ghosh, 2024). While most empirical research to date focuses on other RA system types, many of their documented benefits can reasonably be expected to extend to RP co-cultures (Gale, 2025).

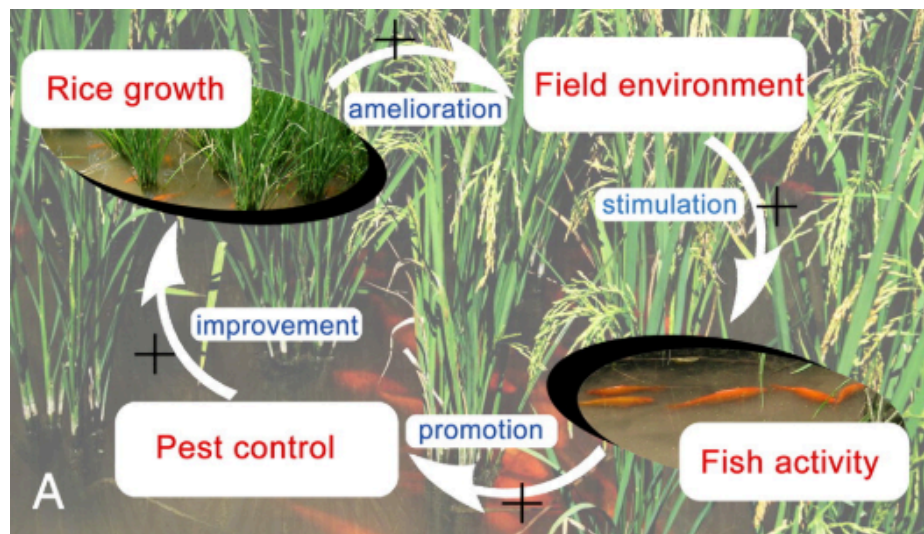
Giant freshwater prawn (*Macrobrachium rosenbergii*), indigenous to Cambodia and particularly abundant along the Mekong River and its tributaries, holds strong economic value and growing market demand (Santos et al., 2017; Phichong et al., 2026). For this reason, RP systems have been promoted by scientists, governments, and development partners as a response to the environmental and economic limitations of monoculture farming (Phichong et al., 2025).

2.2.1. Ecological Mechanisms and Interactions of Rice-Animal Systems

RA co-cultures are not unique to Cambodia but have been reported in China, Egypt, India, Thailand, Vietnam and beyond (Lansing & Kramer, 2011). The mutualistic interactions underpinning these systems are well evidenced in the literature. Prawns, being highly sensitive to chemical inputs, are effective bio-indicators of paddy health (Sumon et al., 2016). Fish presence in rice paddies has been shown to reduce pests, aquatic weeds, and algae. They also control malaria mosquitoes and water-borne disease vectors through predation on flies, snails, and insects which simultaneously reduces the need for external feed inputs (Ahmed & Garnett, 2011; Matteson, 2000; Xie et al. 2011). Rice stalks provide shading that moderates water temperature, while flooded fields supply fish with planktonic and periphytic food sources, and fish feeding movements enhance water aeration and quality (Kunda et al., 2008; Mustow, 2002; Ahmed & Garnett, 2011; Xie et al. 2011). Figure 1 provides an overview of these interactions.

Figure 1

Ecological Mechanisms Supporting Rice-Fish Co-Cultures Showing Mutualistic Pest Regulation



Note. Adapted from *Positive Interactions And Complementary Use Of Nitrogen* [Diagram] by Xie et al., 2011

2.2.2. Environmental Performance: Emissions and Nutrient Cycling

Several studies confirm that RA co-culture systems can reduce CH₄ emissions relative to monoculture systems. Yang et al. (2025) found rice-crab and RF systems reduced CH₄ by ~23%, primarily through suppressed ebullition in stocking ditches (a channel adjacent to the rice paddy in which the prawns have access to deeper water) rather than changes in diffusion, while also achieving higher rice yields and lower yield-scaled emissions. Zhang et al. (2023) similarly reported a ~9.2% reduction, attributed to animal activity increasing soil oxygen and promoting CH₄ oxidation. In RP systems specifically, Liu et al. (2025) identified multiple specific prawn-related mechanisms: deeper pond depth inhibiting CH₄ transport, sediment disturbance reducing methanogenic substrate, and burrowing disrupting anaerobic soil conditions.

However, outcomes vary across system types. Cui et al. (2023) found that while rice-duck and rice-crab systems decreased CH₄, RF systems increased emissions by 29%, linked to an 18% drop in dissolved oxygen from deeper water and higher fish oxygen consumption. Datta et al. (2009) similarly found RF farming elevated CH₄ relative to monoculture, though with a concurrent reduction in N₂O. These contrasting findings suggest that co-culture systems modify CH₄ transport pathways rather than eliminating production, and that outcomes are highly system-specific. Table 1 provides an overview of values provided by academic literature on direct site emissions from rice paddies, aquaculture and co-cultures. In assessing the broad range of numbers provided below, it quickly becomes apparent that CH₄ emissions are largely influenced by site-specific factors such as temperature, wind, sun exposure, and pond chemistry, as well as animal-related aeration.

Table 1*Direct CH₄ Field Emissions*

Types of wetlands	Locations	CH ₄	Unit	Notes	Reference
Crab Ponds	Nanjing, China	68.24	kg ha ⁻¹ yr ⁻¹	NA	Fang et al (2022)
	Changshou, China	53.44	kg ha ⁻¹ yr ⁻¹	NA	Ma et al. (2018)
Fish Ponds	Nanjing, China	42.31	kg ha ⁻¹ yr ⁻¹	NA	Wu et al. (2018)
	Nanjing, China	88.55	kg ha ⁻¹ yr ⁻¹	NA	Fang et al (2022)
Freshwater & brackish ponds	NA	183.00	kg ha ⁻¹ yr ⁻¹	This represents the ‘baseline emission factor’ that needs to be calculated further and is context dependent.	IPCC (2019)
	Indonesia	533.00	kg ha ⁻¹ yr ⁻¹	NA	Henriksson et al. (2019)
Rice Monoculture	Germany	876.00	kg ha ⁻¹ yr ⁻¹	The values were converted to direct annual fluxes converted from mg m ⁻² h ⁻¹ .	Frei and Becker (2005)
	China	458.80	kg ha ⁻¹	Emissions from the first agricultural year	Fang et al. (2023)
	Panjin, China	565.00	kg ha ⁻¹ yr ⁻¹	282.5 kg ha ⁻¹ season ⁻¹ , converted assuming two seasons in one agricultural year.	Wang et al. (2019)
	Southeast China	490.00	kg ha ⁻¹ yr ⁻¹	NA	Liu et al. (2025)
	NA	474.50	kg ha ⁻¹ yr ⁻¹	The ‘baseline emission factor’ is 1.30 kg ha ⁻¹ day ⁻¹ is the and need to be calculated further; context dependent.	IPCC (2006)
	China	315.30	kg ha ⁻¹	Mean value of estimation of field emissions and losses of different farming systems.	Xu et al. (2022)
	Thailand	240.00	kg ha ⁻¹	This number would rise to 456 kg ha ⁻¹ with the incorporation of rice-straw	Silalertruksa & Gheewala (2013)

Types of wetlands	Locations	CH ₄	Unit	Notes	Reference
Rice-Crab Co-Culture	Panjin, China	375.65	kg ha ⁻¹ yr ⁻¹	Average of both fields and converted from seasonal emissions to annual, assuming two seasons in one agricultural year.	Wang et al. (2019)
Rice-Crayfish Co-Culture	China	405.70	kg ha ⁻¹ yr ⁻¹	Emissions from the first agricultural year	Fang et al. (2023)
	Qianjiang, China	397.70	kg ha ⁻¹ yr ⁻¹	NA	Si et al. (2017)
	China	260.70	kg ha ⁻¹	Mean value of estimation of field emissions and losses of different farming systems.	Xu et al. (2022)
Rice-Fish Co-Culture	Cuttack, India	217.25	kg ha ⁻¹ yr ⁻¹	NA	Datta et al (2009)
	Cuttack, India	137.90	kg ha ⁻¹	Averaged across multiple rice fish systems	Bhattacharyya et al. (2013)
	Germany	293.80	kg ha ⁻¹ yr ⁻¹	13.6 mg m ⁻² h ⁻¹ was the value provided, but was converted for direct comparison assuming a 90 day season.	Frei & Becker (2005)
Rice-Prawn Co-Culture	Southeast China	189.00	kg ha ⁻¹ yr ⁻¹	NA	Liu et al. (2025)

Note. A summary of field direct CH₄ emissions and emission factor of CH₄ from aquaculture ponds, rice monoculture and rice-animal co-cultures. Values reported in the literature were expressed in varying units; while conversions have been applied to enable direct comparison in this table, these should be interpreted with caution. This overview is therefore intended for indicative purposes only.

2.2.3. Food Security, Productivity and Soil Fertility of Co-Cultures

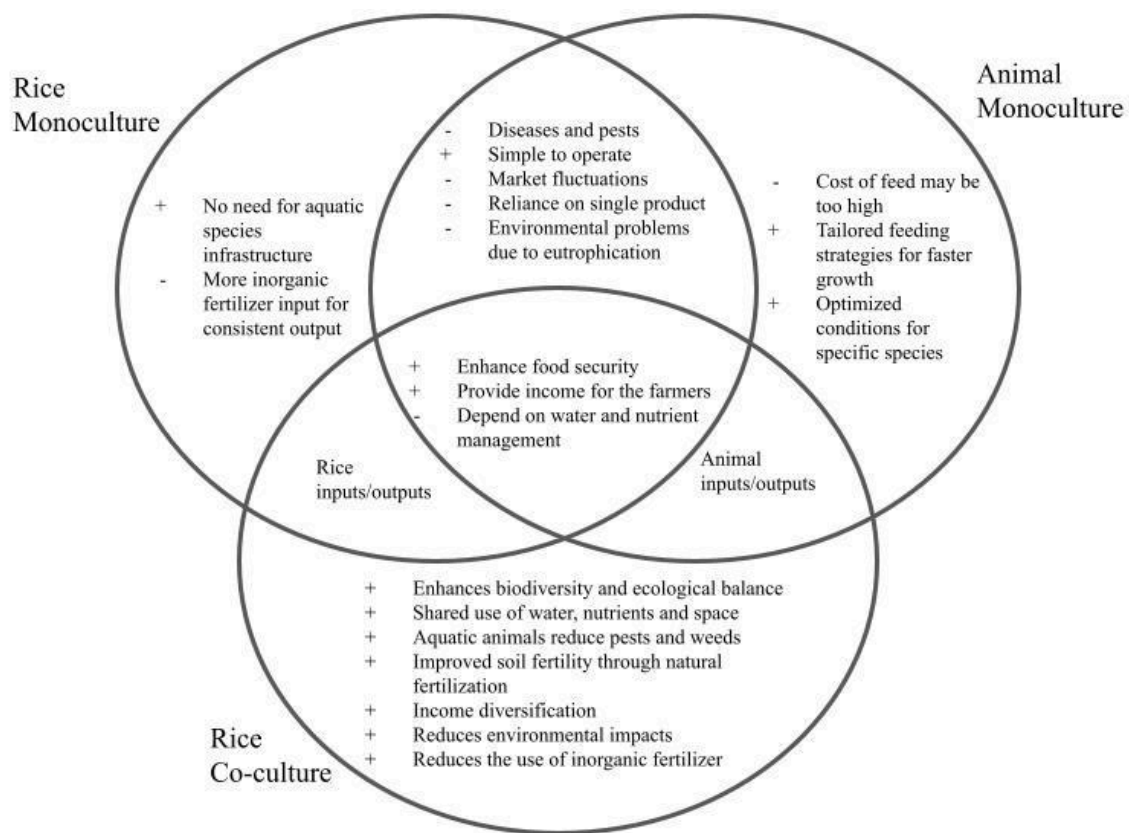
RA co-cultures also demonstrate potential for improving food security and productivity. Ahmed and Garnett (2011) found that RF co-culture enhances resource efficiency, improves soil fertility through increased nitrogen and phosphorus availability, and raises both the quantity and nutritional quality of food outputs relative to monoculture. Their economic analyses suggested even higher yields could be achievable if inputs were increased strategically. Li et al. (2023) similarly found that integrating high-stalk rice into shrimp ponds reduced (CH₄ and N₂O) emissions while maintaining or improving shrimp yields, alongside enhanced oxygen transfer, nutrient cycling, and water quality. In Bangladesh RP

systems provided two to three times higher profits compared to RF systems under similar production conditions, while also supporting food security and generating household income (Mirhaj et al., 2013).

Xie et al. (2011) found that rice-fish co-cultures required 68% less pesticide and 24% less chemical fertiliser than rice monoculture, supported by complementary nutrient cycling between rice and aquatic species that reduces runoff and eutrophication risk. Kamara et al. (2026) further highlight improvements in soil structure, water retention, and microbial activity. Figure 2 provides a visual overview of some of the benefits of such systems.

Figure 2

Venn Diagram of Rice-Coculture Advantages and Drawbacks



Note. Adapted from Venn Diagram Showing the Main Features of Rice-Fish Coculture and Monoculture Systems [Diagram] by Kamara et al., 2026.

At larger scales, Wang et al. (2024) demonstrated through an LCA that RF and RC co-cultures could potentially generate up to 20% of projected freshwater aquaculture protein and 70% of future marine capture protein by 2030. They argued that scaling co-cultures to replace red meat worldwide could avoid around 98 million tonnes of GHG emissions and save 13 million hectares of land. Beyond productivity and emissions, Xie et al. (2011) further highlight co-culture benefits for biodiversity, land and water use efficiency, and cultural significance.

2.2.4. Barriers to Adoption of Co-Culture Systems

Despite the ecological and economic promise of RP co-culture systems, adoption remains limited. Constrained by a combination of technical, biophysical, financial, and socio-cultural barriers, the transition from conventional monocropping quickly becomes unattainable for most smallholder farmers.

Technically, RA systems demand substantially greater management sophistication than monoculture, requiring deeper and stable water levels, irrigation control, and physical field modifications such as trenches and reinforced embankments. Such infrastructure is difficult (and costly) to establish in water-scarce or drought-prone regions (Sathoria & Roy, 2022; WorldFish, 2025). Ahmed and Garnett (2011) highlight farmers' limited technical knowledge, drought vulnerability, and the historical tension between high-yielding rice varieties and pesticide use, which has suppressed fish yields in traditional RF systems. In the Cambodian context, the prawns' heightened temperature sensitivity necessitates close daily monitoring and physical transfer in and out of the rice field; an operational complexity entirely absent from monoculture.

Financially, infrastructure costs (ditch and pond construction, pumps, aerators etc.) can range from USD 3,000 to 10,000 upfront, contrasting starkly with the lower entry costs of monoculture rice (Srean et al., 2018; WorldFish, 2025). Limited smallholder access to credit disproportionately compounds this barrier for those with smaller landholdings (Sathoria & Roy, 2022). Zhang et al. (2023) found that although co-cultures improved the soil's organic carbon and nitrogen storage, and reduced GHG emissions, RC systems produced a 3.9% decline in rice yield relative to monoculture. Additionally, freshwater prawn's high market value also introduces a security dimension, requiring near-constant field surveillance that makes RP unsuitable for those unable to maintain consistent farm presence. Paradoxically, this same characteristic renders RP well suited to women smallholders, for whom the system's low physical intensity is compatible with domestic responsibilities (Phichong et al., 2026).

Socio-culturally, familiarity with monoculture, fear of yield loss, and uncertainty around prawn market access (particularly given competition from cheaper imported alternatives) fortify resistance to transitions (Phichong et al., 2026). As outcomes vary across system types, with some integrated systems associated with increased CH₄ emissions, and some with lower productivity, suitability is heavily context-dependent (Wan et al., 2019). Taken together, these barriers help explain why RP co-culture has seen slow uptake since its introduction in Cambodia in 2021, and underscore the importance of empirical, context-specific assessment such as that conducted in this study. However, these drawbacks do not inherently point to RP co-cultures being inapplicable to the increasingly important sustainable agricultural transition in Cambodia. Instead, it highlights that co-culture systems' advantages may be heavily case dependent.

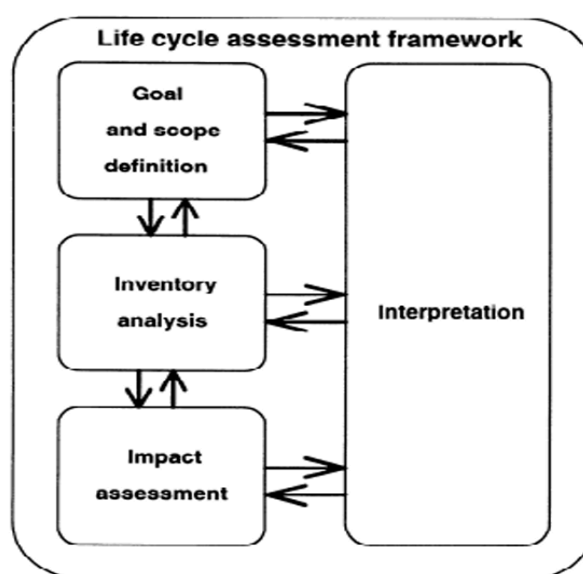
2.3. Research Gap and LCA

While the reviewed literature demonstrated the ecological and productivity benefits of RA co-cultures, a notable research gap remains. Most existing research focuses on other RA systems, whereas integrated RP systems (despite their growing relevance) are comparatively underexamined. This is a critical omission because as shown in the literature review, conventional prawn and rice farming are both widely associated with high environmental pressure. Very little empirical evidence exists on the environmental footprint, biodiversity outcomes, or long-term viability of RP systems. This gap is especially pronounced in research using LCA methodologies, which have rarely been applied to integrated RP systems and so this insight into their full-system environmental impact is lacking. Collaboration with the international NGO WorldFish enabled the generation of novel empirical data on RP interactions, supporting rigorous assessment of their environmental performance and potential as a sustainable agricultural alternative.

LCA is a quantitative method used to evaluate the environmental impacts of a product or service across its value chain to identify opportunities to reduce environmental burdens (Baumann & Tillman, 2004). An LCA typically follows a cradle-to-grave perspective, assessing environmental impacts from raw material extraction to end-of-life (EoL) (ISO, 2006). For studying fisheries and aquaculture, LCAs are often applied to help identify emission hotspots and improve environmental sustainability. More information on the LCA methodology, its constituent phases, and the potential drawbacks can be found in Appendix B. LCA's distinct phases are aligned with ISO 14040/44 standards. This standard, depicted schematically in Figure 3, divides LCA studies into four methodological phases: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation.

Figure 3

Schematic Representation of the LCA Procedure



Note. From The Distinct Phases of the ISO Standard [Diagram] by ISO, (2006)

2.4. Research Questions

In order to fill the research gap and fulfil the objective of my research, I have defined the following research question.

“What are the environmental impacts and life cycle hotspots of rice-prawn co-culture farming systems compared to conventional monoculture rice production systems in Cambodia over one agricultural cycle across both of their life cycles?”

2.4.1. Sub-Research Questions

To operationalise the main research question, I answered several sub-research questions, each linked to specific methodological steps outlined more thoroughly in Chapter 3. The following are the sub-research questions:

Q1: What are the average environmental impacts from the dry season and wet season across all farms? And is there a positive correlation to seasonal variability between farms?

Q2: Which processes and environmental flows contribute most significantly to the environmental impacts of integrated rice-prawn co-culture systems versus rice monocultures?

Q3: How do these two product systems compare across relevant environmental impact categories?

Q4: How sensitive are the results to variations in key parameters?

For a more in-depth explanation of the research objective and its link to the discipline of Industrial Ecology, please see Appendix A.

3.

Materials and Methods

To address my Research Questions, my research approach combined field-based data collection, and LCA modelling. Firstly, I will outline the fieldwork methodology and then I will explain the LCA approach.

3.1. Fieldwork Methodology

I used primary data collected through fieldwork and existing WorldFish databases to create the model for the RP co-cultures. Primary data were collected through WorldFish's existing network of relevant stakeholders within the RP and monoculture rice farming process. Four Cambodian RP farmers located in Kampong Thom were interviewed following a semi-structured format. See Appendix D for a more detailed description of how the sampled subjects were selected, and the WorldFish framework that they are situated within. For the monoculture rice system, data were gathered from two farms: one operated by a farmer who was interviewed as an RP farmer, and one farmer who exclusively practices rice monoculture.

3.1.1. Farm Identification Nomenclature

The identification code for each farmer is displayed in table 2, which also distinguishes between fields and production cycle being assessed. The RP code follows as “farmer_number . field_ID . production_cycle_number”. For instance, the first farmer's field A's first cycle would be written as: 01.A.01. For clear distinction between monoculture and RP farmers, the monoculture farmers are all grouped under the farmer ID “05”, with the distinctions between fields and cycles following the RP ID system (all monoculture farmers considered only had one monoculture field). It must be noted that different production cycles within the same field are not treated as independent data points or pseudo replicates.

Table 2*Rice-Prawn ID Codes*

Rice Prawns ID		
Farmer ID	Field	Cycle
01	A	01
		02
	B	01
02	A	01
03	A	01
04	A	01

Note. Detailing the Rice-Prawn ID codes used in this paper to distinguish among farmers, fields and cycles

In total four RP farmers were interviewed. Of these, only farmer 01 had completed a full agricultural year (i.e. two production cycles). The other three farmers (02, 03 and 04) were, at the time of the interview, still in the process of completing their second production cycle.

Table 3*Rice Monoculture ID Codes*

Rice Monoculture ID		
Monoculture ID	Farmer and Field ID	Cycle
05	A	01
		02
	B	01
		02
	C	01

Note. Detailing the Rice Monoculture ID codes used in this paper to distinguish between farmers, fields and cycles

Additionally, two monoculture farmers were interviewed (05.A and 05.B.) seen in Table 3. This smaller sample size follows as more existing research has been conducted on monoculture farms, thus previous LCA studies and other secondary data sources, notably those from WorldFish's internal datasets, will be used to create the product system. The third rice monoculture field considered (05.C.01) in my dataset was based on reports of common farming practices from the interviewed farmers' knowledge of nearby farming practices, and was constructed to expand the small sample size. Furthermore, monoculture farmer farmer 05.A. and RP farmer 04 represent the same farmer, who has both a monoculture rice plot and a RP lot.

3.1.2. Interviews

I conducted two semi-structured interviews per RP farm, the first to gather the majority of the information and the second, at a later point in time, was used in order to fill the remaining data gaps as well as to validate the initial data. The second interview was conducted after the completion of the three farmers' first agricultural year (farmers 02, 03, and 04) and used to fill knowledge gaps. The semi-structured interviews were conducted following the structure of the interview guide (see Appendix E, F and G). This guide was based on the extensive survey format examples provided to me by my supervisor, Patrik Henriksson, and adjusted to fit the context of my thesis. Each interview lasted around 90 minutes and the answers were recorded on a printed interview guide. The interviewee was introduced to me by the translator and was given an explanation of the purpose of the project. All questions were asked sequentially, leaving room for certain topics to be expanded upon or skipped entirely if no answer was possible.

Additional semi-structured interviews were conducted to gather specific data on related unit processes (UPs), where possible. In total, two additional interviews were conducted: one with the prawn hatchery that supplies the RP farmers (conducted over the phone), and the other with the prawn feed supplier (see Appendix D and C for the respective interview guides).

As the interviewees did not speak English, a WorldFish staff member interpreted between English and Khmer. The interpreters all had prior experience working with the participating farmers, which facilitated communication and contextual understanding. The use of interpreters introduced methodological limitations, including the inability to verify responses against recordings, occasional supplementation of participants' answers by the translator, and the inevitable loss of nuance during translation. To address these limitations, I triangulated the data by cross-referencing interview responses with existing datasets from WorldFish. However, such data were only available for 01.A.01 and 01.A.02 as well as 05.B.01. Furthermore, in some cases, additional data (such as yield figures from subsequent harvests) were only available during the second round of interviews and therefore could not be independently validated.

3.1.3. Study Area Description

My research took place in the same area as the WorldFish pilot was implemented: in Chey Chum Neas Village, Santuk District, Kampong Thom Province, Cambodia. This area is influenced by seasonal flooding from the Tonle Sap Lake, creating favourable agroecological conditions for integrating rice cultivation with aquatic production (Phichong et al., 2025). Table 4 provides a breakdown of the RP farms.

Table 4*Rice-Prawn Farmers' Field Size and Total Production*

Farm ID	District and Province	Total Farm Area (m^2)	Total Rice-Prawn Area (m^2)
01	Suntuk, Kampong Thom	58000	8200
02	Suntuk, Kampong Thom	143500	3500
03	Suntuk, Kampong Thom	10400	5800
04	Suntuk, Kampong Thom	17490	6000

Next, a description of each farmer, their land and relevant agricultural details will be discussed.

Table 5*Description of Rice-Prawn and Rice Monoculture Farms*

Category	Rice-Prawn				Monoculture Rice		
Farmer ID	Farmer 01	Farmer 02	Farmer 03	Farmer 04	Farmer 05.A	Farmer 05.B	Farmer 05.C
Location	Kor-Koh Village, Kampong Thom, Cambodia						Kampong Thom, Cambodia
RP plots	2	1 (expanding to 3)	1 (expanding to 3)	1	NA		
Share of farmland	14%	24%	55%	27.3%	45.4%	33.3%	NA
First cycle started	Dec 2024	Sept 2025	Aug 2025	Sept 2025	>40 years ago	>35 years ago	NA
Cycles completed	2 (full year)	1 (2nd ongoing)			30 years+ with 2 per year	40 years+ with 2 per year	2/year
Stocking ditch shape	U-shaped				NA	NA	NA
Rice variety	5154 → Tubtim Chum Phae	Tubtim Chum Phae	Phka Rumduol → Rieng Chey	5154	Rumdoul & Tibitim Chumphae	Rumdoul & 5154	Rumdoul & Tibitim Chumphae

Category	Rice-Prawn				Monoculture Rice		
Prawn Species	M. Rosenbergii				NA	NA	NA
Notes	Only farm with full year completed at time of interview	Plans to expand	Switched rice variety after first harvest	Water access cut off before second RP cycle; fell back to monoculture	Also farms catfish-rice and vegetable plots	Rest of farmland is cashew plantation	Modelled from 05.A & 05.B descriptions of neighbour's farms and WorldFish internal data

Figures 4-6

Farmer 01's Farmhouse and Rice-Prawn Paddies



Figures 7-8

Farmer 02's Rice-Prawn Paddies



Figures 9 - 10

Farmer 03's Freshwater Prawn Harvest



3.2. Life Cycle Assessment

3.2.1. Goal

The goal of my LCA research is to assess and compare the potential environmental impacts of RP co-culture in comparison to rice monoculture in Cambodia (see Appendix A for a more detailed explanation). Ultimately, it aims to provide transparent, evidence-based information to identify whether RP co-cultures are more environmentally sustainable across their lifecycle than the more common, monoculture, practices. To conduct the LCA I compared RP farms to the traditional monoculture rice farms found in Cambodia. Table 6 below shows a breakdown of the time to harvest, the number of harvests, the protein content and the economic value per kilo at the farm gate of the two output products.

Table 6

Breakdown of Processes

	Freshwater Prawn (approximate values)	Rice (approximate values)			
Species/Variety	Macrobrachium rosenbergii	5154	Tubtim Chum Phae	Rieng Chey	Phka Rumduol
Agricultural Cycle	~6 months	~3 to 4 months			
Average Number of Annual Harvests	2 harvests	2-3 harvests			
Protein Content (g per 100g)	17.5g per 100g (Institute of Nutrition, 2014) 23.93 % (Siva Reddy et al., 2013)	7.9g per 100g (Amru Rice, n.d.)	9.56g per 100g (Plaitho et al., 2026)	6.7g (milled rice) (Zhao et al., 2016)	8g (milled rice) (Zhao et al., 2016)
Energy (kcal)	108 (Institute of Nutrition, 2014)	346 (Xu et al., 2022)			
Economic Value at Gate (USD per kg)	15	0.175	0.25	0.375	0.375

With this study I aim to support Cambodian farmers, governmental officials and NGOs in making informed, environmentally conscious decisions regarding which farming practices to continue to promote. It can help to identify key hotspots where interventions can further

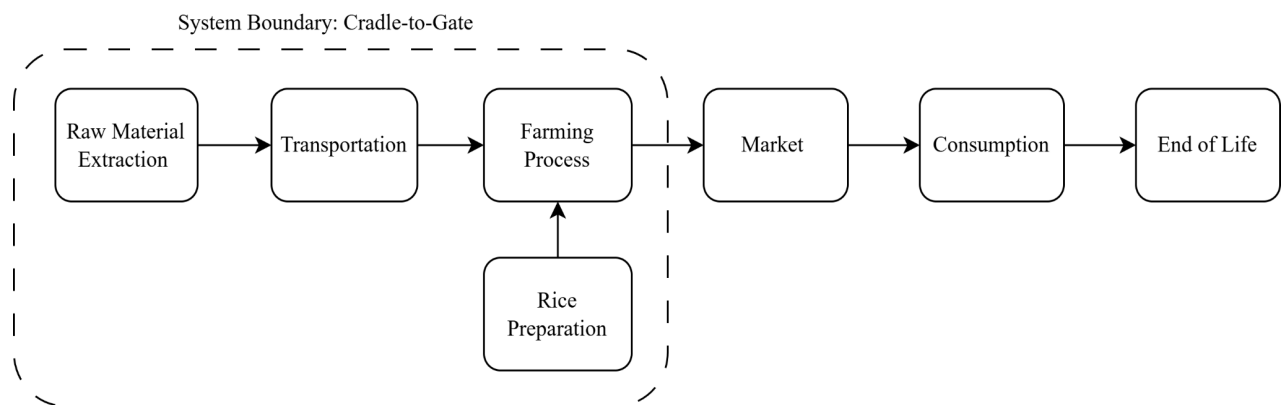
reduce environmental impacts. While the results of this LCA are intended for use within WorldFish, further analysis is needed for comparative assertions disclosed to the public. The audience of the report is therefore predominantly academic and institutional who can utilise and expand on the LCI dataset for further analysis.

This study constitutes my master thesis under the MSc Industrial Ecology jointly offered by Leiden University and Delft University of Technology. It is performed independently, but is commissioned by WorldFish Cambodia. It is not financed by any external organisation. The University Supervisors acted as the steering committee and expert reviewers (see Appendix D for the table of involved parties).

3.2.2. Scope

My study conducts an attributional LCA where environmental burdens are assigned to each product, making it suitable for comparing product-specific impacts. To overcome the previously defined research gap, I studied RP co-cultures and rice monoculture within the context of the Cambodian Market in 2026. Thus, the scope of my LCA is the rice and prawn industry and its related input product chains (such as fisheries, electricity, agriculture, etc). The study covers part of the life cycle of both products, from raw material extraction (cradle) up to the point where the product leaves the farm (gate), see figure 11 for a simplified model of the system boundary. This modelling choice follows due to lack of specific data from the gate-to-grave processes, as well as the time constraints of a master thesis.

Figure 11
Simplified System Boundary



End-of-life processes, wastewater treatment, and intermediate and post-farmgate packaging were excluded from the system boundary. Transport processes, including distribution from material sourcing to the production site were included.

3.2.2.1. Temporal and Geographical Scope

The farmer 01 started their first RP agricultural cycle in 2024, however at the time of data collection, the majority of participating farmers had just transitioned into RP farming and were still completing their first agricultural cycle. Consequently, a full agricultural year of data could not be recorded for many farms, resulting in limited data availability and representing an inherent constraint on the comprehensiveness of the empirical dataset.

The geographic boundary of my study includes Cambodia for downstream processes and the primary production countries, mainly Vietnam, for upstream processes, reflecting the international nature of the supply chain. Ongoing border tensions between Cambodia and Thailand have resulted in most imports now being sourced from Vietnam. Therefore, this thesis, conducted in 2026, models current supply chain conditions as accurately as possible while acknowledging that trade patterns may change if the situation stabilizes.

All farms included in my study are located in Kampong Thom Province in central Cambodia and are situated in close proximity to one another and lying within the Tonle Sap floodplain (see figure 12 for the rough catchment area of the farms).

Figure 12

Map of Farm Catchment Area in Kampong Thom Province, Cambodia



Note. Map of farm locations catchment area within the orange circle, showing relative proximity to the Tonle Sap water body (lower-left of the picture)

3.2.3. Function, Functional Unit, Alternatives, Reference Flows

Field sizes and trenches, rice varieties and seasons vary across the studied farms, resulting in differences in rice and prawn production volumes, making each field in each farm unique. In addition, some farmers operated multiple fields and cultivated different rice varieties simultaneously, further complicating the definition of a consistent functional unit.

In Table 7, the function, functional unit, alternatives, and reference flows of the two alternatives are presented.

Table 7

Function, Functional Unit, Alternatives, and Reference Flow

Function	Providing agricultural products to consumers in Cambodia	
Functional Unit	Providing agricultural products to consumers in Cambodia over one agricultural cycle from one field.	
Alternatives	Rice Prawn Co-culture Farming System	
	Monoculture Rice Farming System	
Reference flows	Mass: 100kg equivalent	Providing 100.00 kg of prawn to consumers in Cambodia for one agricultural cycle from one field.
		Providing 282.34 kg* of rice to consumers in Cambodia for one agricultural cycle from one field.

*See Appendix F for an explanation of this equivalent and an in depth explanation of the choices behind the reference flows

The temporal boundary of the study was defined such that one product system represented one field over one production cycle, allowing for a standardized comparison across farms despite differences in field size and crop variety. Thus, each production crop was used as an individual agricultural cycle allowing it to represent the nuances of certain situational and environmental conditions such as temperature, precipitation level or water management.

3.2.4. Life Cycle Inventory

This study used an ALCA methodology with a cradle-to-farmgate framework. In this phase, the collected data were processed into openLCA models for both the integrated RP system and the monoculture reference system. Background processes were sourced from Ecoinvent. Environmental Footprint (EF v3.0) was used as the primary LCIA method due to its comprehensive midpoint coverage. The impact categories (ICs) (within the impact family E.v. 3.0) considered in this paper were: Acidification (mol H⁺-Eq), Climate Change (kg CO₂-Eq), Eutrophication: freshwater (kg P-Eq), Land Use (dimensionless) and Water Use (m³ world Eq deprived). The selection of these ICs represents a trade-off between data availability, diversity of inventory flows, and differences in uncertainty across ICs. The results from the other ICs can be found in the Supplementary Materials (SM)

3.2.4.1. Economy-Environment System Boundary

Following Guinée et al's (2002) convention, in order to distinguish between the economic and environmental system, the boundary was drawn at the point where flows enter or leave human control. In my study, any background processes maintain the economic-environmental boundaries already drawn by the Ecoinvent database. Thus, any related natural processes were treated as environmental flows and were therefore not assigned to the economic system. To ensure consistency, the same boundary logic was applied to the foreground system.

3.2.4.2. Cut-offs

Capital goods were cut-off within all the foreground processes. Additionally, processes estimated to contribute less than 1% of the whole system were cut-off. Manure was not allocated any environmental impacts from animal farming/raising as the manure was deemed to hold no monetary value (see Appendix I for further explanation). As RP farmers used hand processing measures, such as hand-tilling, they were also cut-off. Rice husking and milling were combined into a single process. Rice husking and milling were modelled as a single process, while by-products consumed outside the system boundary, including broken rice, rice polish, (most) rice husks and bran, and by-products from capture fisheries and fishmeal processing, were excluded.

EoL processes, wastewater treatment following discharge, and packaging beyond the farm gate were excluded as they occurred outside the system boundary and often had limited data availability. This included primary consumables such as secondary and tertiary packaging, and packaging of intermediate products, meaning that the packaging of semi-finished or intermediate products, such as plastic bags used to transport snails from the village to the farm, were excluded. The limitations of the LCA methodology in terms of biodiversity assessment, particularly in relation to the golden apple snail can be found in Appendix K. Transport modelling, however, included the distribution of primary packaged products from material sourcing to the production site — where not already represented in the Ecoinvent background processes.

Land occupation was quantified as hectares occupied per year in each field for each cycle, while land transformation impacts were excluded (Müller-Wenk & Brandão, 2010). Given the long-established history of rice cultivation within the Tonle Sap floodplain, where agricultural land use in many regions predates modern record-keeping and in some areas was enforced under historical political regimes — it was assumed that these fields have been under continuous agricultural use for generations. As such, land conversion was considered negligible for the study area.

Any incomplete agricultural cycles were excluded from the analysis. This includes cycles where both rice and prawn had not yet been harvested at the point of data collection, and one farm (04) where prawn were not stocked due to water shortage. Broodstock transport was modelled for a single six-month cycle, as no data were available on the frequency of imports these were cut off.

3.2.5. Life Cycle Impact Assessment Data

As discussed in Chapter 2, CH₄ is important to accurately measure within my LCA. Given the economic and time constraints of my thesis, direct field measurement of CH₄ was not feasible, and proxy-based calculations were therefore employed. For the Monoculture systems the IPCC emission calculation factor for flooded rice paddies was chosen as the most applicable, as it can be adjusted to each product system. Applying a baseline of 1.3 kg ha⁻¹ d⁻¹ and adjusting it by scaling factors (see SM S&T for the full calculation).

For the RP co-culture systems, however, this approach was insufficient. As outlined in the literature review, the introduction of prawns into the paddy can substantially alter CH₄ emissions, making the standard IPCC estimate inappropriate for integrated systems. Based on the literature review, the system studied by Liu et al. (2025) resembled mine the closest, as they also focused on freshwater prawn and rice. Thus, I scaled emissions from Liu et al.'s (2025) 189 kg ha⁻¹ y⁻¹ value to be relevant to the correct area and temporal scale of each product system (see SM R). While this figure does not fully account for site-specific environmental discrepancies between locations, it represents the most contextually appropriate value available in the current literature.

With respect to specific inputs, I modelled rice seed reuse on farmer-reported intentions for subsequent cycles. Where farmers confirmed reuse across three cycles, seed procurement was modelled as 50% purchased and 50% retained from the previous cycle. I assumed an additional 10% seed surplus to be stored for the next cycle, as well as a harvest-to-straw ratio of 1.255:1 (Kumar et al., 2022). Revenue data was primarily gathered through the interviews, however where data were not available economic data were taken from Henriksson et al. (2015) and scaled for inflation (using a scaling factor of 1.302, derived from the Cambodian Consumer Price Index (World Bank, 2025)). A currency conversion rate of 1 USD = 4,000 Cambodian riel was applied throughout.

Prawn feed for the RP system was split between two feed types at an approximate 40:60 ratio. These two feed types represent a broader range of pelleted feed types (all from the

same company) used across the farms. However, the feed shared near-identical compositional profiles (differing only in pellet size as far as could be determined) and ingredient lists were consolidated into two representative categories for modelling purposes (see SM AO). Squid and fish meal inputs were assumed to derive equally from large-scale and small-scale fisheries, as collecting data on actual procurement practices was out of the scope of this research. Squid production was modelled as a proxy using anchovy meal data, given the absence of specific squid meal datasets in Ecoinvent.

The water conditioners used within the systems were treated as follows. For dolomite application, I used an emission factor of 0.13 kg N₂O per kg (IPCC, 2006). No additional CO₂ emissions were assigned to quicklime application, as calcination emissions were accounted for in the upstream production inventory. I modelled eutrophication using an adjusted spreadsheet provided by Henriksson et al. (2014) (see SM U - AE). Within this spreadsheet I assumed that 46.9% of excess phosphorus accumulated in sediments and 53.1% was lost via effluent water, with 50% of sediment-bound nutrients eventually released into the surrounding environment. I used data from Henriksson et al. (2014) to model the burning of rice straw (as occurs in product system 05.C.01).

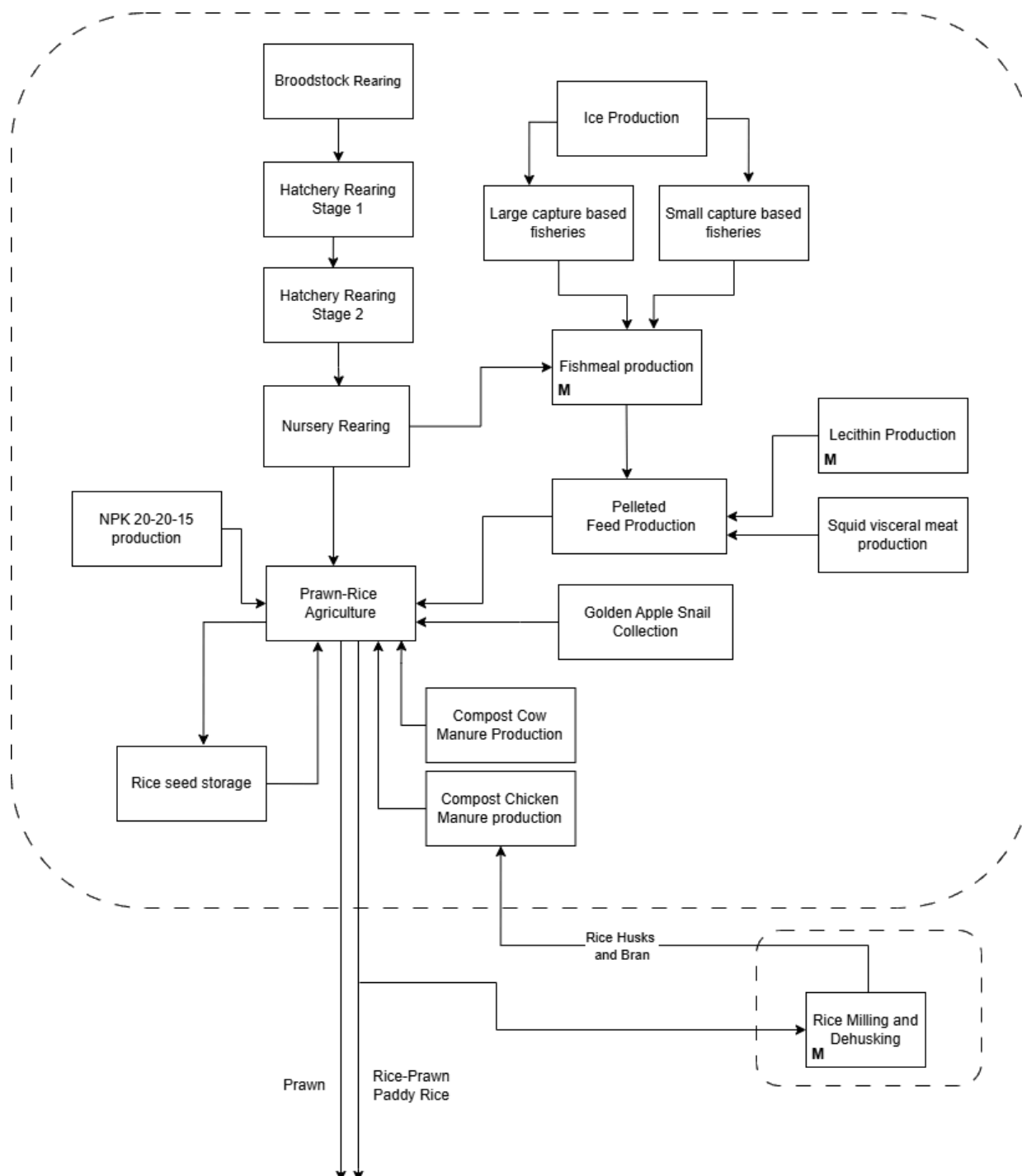
I modelled the water pumping regime based on a single representative pump configuration, scaled across farms according to reported hours of operation, fuel consumption or electricity use, as appropriate to each farm's energy source (see SM Q). As the temporal scope was limited to between 2024 and the present day, the climate data for Kampong Thom was considered in the water use calculations (see Appendix L).

Transportation of inputs was modelled assuming origin from Ho Chi Minh City via the Mekong Delta for most fish products, with Cambodian and Vietnamese trucks assumed to comply with EURO 4 emission standards (CCAC, 2023). All farm inputs that were sourced from the local market were assumed to be transported 2 km from local markets to farms by motorcycle.

3.2.6. Rice-Prawn Flowchart

Figure 13

Simplified Flowchart Representing a Rice-Prawn Product System



Note. See Appendix G for the detailed flowchart

3.2.7. Multi-functionality and Allocation

Allocation strongly influences the results of RP systems, as environmental burdens must be accurately distributed between co-products. Yet, distinguishing contributions of individual inputs is often challenging as many are used both by rice and prawns, but each to different extents. Thus, mass-allocation was consistently applied for all UPs in the foreground data (see Appendix H). Unlike economic allocation, which is sensitive to fluctuating and region-specific prices, mass allocation provides greater consistency and comparability. This was particularly relevant in my research, as many farmers consumed rather than sold their rice, and market prices were highly variable, especially during the 2026 Middle East fuel crisis. Allocation followed a cut-off approach for EoL impacts, replicating the Ecoinvent background processes approach. Furthermore, goods and waste flows were classified based on their market value specifically as flows with a positive economic value ($\text{price} \geq 0$) were designated as goods, whereas flows with a negative value were treated as wastes.

A limitation of LCA is that allocation assigns co-products the same environmental burden per unit at the farm-gate, enabling system-level comparisons but obscuring species-specific differences. To minimise this effect, inputs exclusively attributable to a single product (e.g., rice seed and prawn post-larvae) were allocated entirely to that product. For ‘shared’ inputs, such as prawn feed, 85% of the burden was allocated to the product driving the input and 15% to the co-product to account for potential indirect uptake (e.g., nutrient absorption by rice from uneaten feed). An example of this allocation for field 01.A.01 under mass allocation is provided in Appendix H.

3.2.8. Sensitivity Analyses

Sensitivity analysis evaluates the result's robustness by assessing how variations in process data and modelling assumptions influence the outcomes. Three sensitivity analyses were conducted:

1. Allocation Method: Economic

Mass allocation disregards both the biological requirements of different species and their relative economic value, which can produce counterintuitive results. Therefore, economic allocation was evaluated as the first sensitivity analysis, with the two approaches representing the principal allocation methods in LCA and providing a meaningful range for interpreting the robustness of the results (see SM L).

2. Functional Unit: Market Value

The second sensitivity analysis follows the change in the reference flow to compare the alternatives based on 100 USD of market value (MV), as shown in table 8.

Table 8

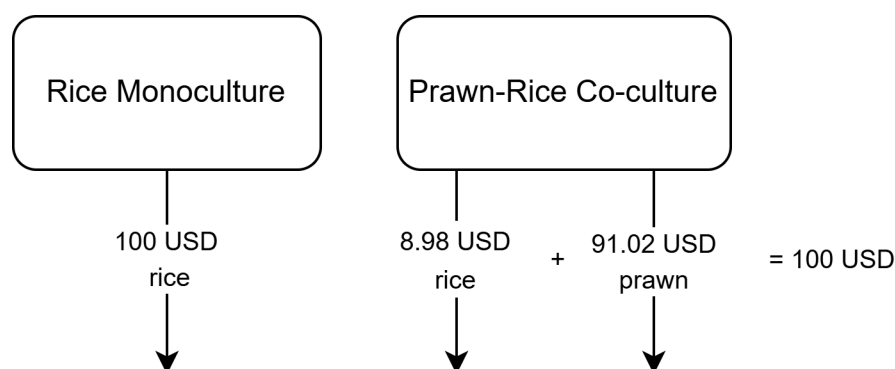
Reference Flows for Market Value Sensitivity Analyses Under Two New Functional Units

Market Value: USD 100 equivalent	Providing \$100 of prawn and rice to consumers in Cambodia for one agricultural cycle from one field.
	Providing \$100 of rice to consumers in Cambodia for one agricultural cycle from one field.

This was calculated by setting the total output revenue to 100 USD and finding the equivalent ratio of rice and prawn per product system. This approach encapsulates the price fluctuation of rice per product system, variety and seasonal variability. Additionally, rice produced in RP systems can be marketed as organic, commanding a higher MV than the same rice strain grown in monoculture fields. A simplified visual of this calculation is provided in figure 14.

Figure 14

A Diagram of the Market Value FU Calculation



Note. A simplified diagram of the scaling used to calculate the rice and prawn market value, representing product system 01.A.01

The change in FU also necessitated a change in allocation practices in order to adequately ascertain the system level environmental burdens. For RP system level emissions, I set the allocation to place 100% of the environmental burdens on the rice and then set it as the functional flow. I could then manually allocate during the analysis based on the selected functional unit.

3. Functional Unit: Nutritional Density Unit

The Nutrition density unit (NDU) was developed by Dooren (2016) and is used in this study as a sensitivity analysis to characterise nutritional differences between the farming systems. As RP and monoculture systems produce different primary outputs, mass or value-based functional units common in LCAs may not provide the most meaningful basis for comparison. Thus, replacing such FUs with nutritional metrics, such as protein, energy or compound vitamin scores could allow the LCA to shift its focus to nutritional quality rather than amount produced. Further advantages also lie in uncovering the correlation between environmental integrity and human health, which is particularly important in the context of Cambodia. Thus, I altered the functional flow as seen in table 9.

Table 9

Reference Flows for NDU Sensitivity Analyses Under Two New Functional Units

Nutritional Value: 1 NDU equivalent	Providing 1 nutritional density unit of prawn and rice to consumers in Cambodia for one agricultural cycle from one field.
	Providing 1 nutritional density unit of rice to consumers in Cambodia for one agricultural cycle from one field.

I calculated the NDU for one product using Equation 1 and used the result in Equation 2 to find the system level NDU.

$$NDU = \frac{\frac{EFA}{DV_{EFA}} + \frac{Protein}{DV_{protein}} + \frac{Fibre}{DV_{fibre}}}{3 \times \frac{S_i}{2000 \text{ kcal}}}$$

Equation 1

$$System \ NDU = \sum_{i=1}^n Y_i \times \beta_i \times Product \ NDU_i$$

Equation 2

where EFA (g) is the amount of essential fatty acids in 100g of product, while protein and fibre (g) similarly represent the amounts in 100g of product. The DV_i are the recommended daily value intakes of EFA, protein, and fibre in grams respectively; and S_i is the amount of kcal in 100 g of product.

Equation 2 shows how to calculate the system NDU, which allows a RP system to be directly compared to the monoculture alternative. Here Y_i represents the yield of each product per product system in kg ha⁻¹ and β_i represents the edible portion of each output product in percentage. To see the calculation of each system and product see SM A. The allocation of this system followed that of the MV sensitivity analysis.

4.

Results

This chapter analyses and presents the collected empirical data in order to assess comparative environmental sustainability of RP vs monoculture systems. The first sub-chapter analyses the raw data, the second looks at the results of a mass FU of 100kg equivalent. Finally, the third sub-chapter visualises the results under three different sensitivity analyses. The first changes the allocation from mass to economic allocation, the second and the third sensitivity analysis change the functional unit from the mass based 100kg to a market-value based unit of 100 USD and a nutritional density unit respectively.

4.1. Analysis of Primary Data

The economic UP data for ‘Rice-Prawn Production’, at the farm-gate is presented in table 10.

Table 10

Direct Economic Inputs and Outputs for Unit Process ‘Rice-Prawn Production’ at the Farm-Gate

Flow	Direction	Amount						Unit
		01.A.01	01.A.02	01.B.01	02.A.01	03.A.01	04.A.01	
[G0253] petrol, unleaded, burned in machinery	Input	684	684	684	2242.54	2565	1179.9	MJ
[G0358] rice seed, for sowing	Input	10	10	5	9	10	19	kg
[G0519] dolomite	Input	25	25	15	125	250	210	kg
[G1712] quicklime, in pieces, loose	Input	125	125	100	125	250	120	kg
[G2527] electricity, low voltage	Input	491.40	247.35	544	NA	NA	NA	kWh
[G0304] water pump operation, diesel	Input	NA	NA	NA	2242.54	2700	NA	MJ
Boiled Corn	Input	NA	NA	NA	NA	30	NA	kg

[G3028] transport, passenger, motor scooter, fleet average	Input	30	40	20	20	30	40	p·km
[G3073] transport, freight, lorry, 16–32 metric ton, diesel, EURO 4	Input	24.5	36.68	6.01	21.67	60.50	63	t·km
Chicken Manure Organic Fertiliser	Input	329.6	37.67	205.84	NA	NA	NA	kg
Cow Manure Liquid Compost	Input	200	NA	200	327.86	1200	200	l
Machrobachium Rosenberggii from Nursery	Input	6728	7000	3000	5200	754	9900	Item(s)
NPK (20-20-15)	Input	10	NA	4	5	NA	5	kg
Pelleted Prawn Feed	Input	40	100	5	40	200	100	kg
Pelleted Prawn Feed	Input	60	60	15	60	100	50	kg
Prawn Feed: Crushed Snails	Input	2000	4000	1200	3484	6000	5135	kg
Rice Seed	Input	10	10	5	9.0	10	19	kg
Machrobachium Rosenberggii	Output	118	294	150	164	226	265	kg
Rice Prawn Paddy Rice	Output	998	600	200	500	30	500	kg
[W0360] municipal solid waste	Output	0.8	0.96	0.48	1.40	2.43	0.45	kg

The table reveals considerable variation in inputs and outputs across product systems. For instance, 01.A.01, 01.A.02 and 01.B.01 have significantly lower petrol and diesel consumption, because a solar panel was installed for this farmer, which powers the water pump (used in all fields). Note that 01.A.01 and 01.A.02 are two cycles in the same field, and should not be interpreted as independent data points or pseudo-replicates. The data show across systems, the level of input does not necessarily correlate to the level of output. For instance, 03.A.01 only produced 30kg of paddy rice, due to a rat infestation in the field. Furthermore, table 11 provides the correlation between prawn output of the different systems and the inputs of prawn

Table 11*Feed Input and Total Prawn Harvest*

System ID	Total Feed Input (kg)	Total Prawn Harvested (kg)
01.A.01	2100	118
01.A.02	4160	294
01.B.01	1220	150
02.A.01	3948	164
03.A.01	6330	226
04.A.01	5285	265

Table 12 provides the per hectare productivity of the different systems, irrespective of their individual conditions.

Table 12*Productivity of Each Product System in Kilograms per Hectare.*

Plot Type	System ID	Plot size (m2)	Harvested Rice (kg)	Harvested Prawn (kg)	Productivity (kg/ha)
Rice-Prawn	01.A.01	5500	998	118	1212.55
	01.A.02	5500	600	294	1134.55
	01.B.01	2700	200	150	755.56
	02.A.01	3500	500	164	968.57
	03.A.01	5800	30	226	419.66
	04.A.01	6000	500	265	941.67
Average					905.42
Monoculture Rice	05.A.01	10000	3000	NA	3000
	05.A.02	10000	4000	NA	4000
	05.B.01	10000	3000	NA	3000
	05.B.02	10000	2000	NA	2000
	05.C.01	10000	4000	NA	4000
Average					3200

This allows for a simplistic overview of the different productivity variations across the systems. The total output of a system, however, does not relate directly to its environmental impact. Table 13 displays the environmental inputs and outputs of the RP systems.

Table 13*Direct Environmental In- and Outputs per Production System*

Flow	Direction	Amount						Unit
		01.A.01	01.A.02	01.B.01	02.A.01	03.A.01	04.A.01	
[E9597] Water, river	Input	90200	46997.82	100179.01	64900.53	270263.62	62011.12	m ³
[E9604] Occupation, annual crop, flooded crop	Input	2305	2305	1790.13	1467.12	3575.34	3402.74	m ² ·a
[E2036] Ammonia	Output	32.86	32.86	32.86	5.91	98.35	4.48	kg
[E2172] Carbon dioxide, non-fossil	Output	3.25	3.25	3.25	16.25	32.5	27.3	kg
[E2383] Dinitrogen monoxide	Output	4.47	4.47	4.47	0.8	13.39	0.61	kg
[E2723] Methane, non-fossil	Output	51.83	51.83	51.83	35.34	67.57	64.31	kg
[E5811] Nitrogen (soil)	Output	16.50	16.50	16.50	3.47	46.82	4.93	kg
[E5870] Phosphorus (soil)	Output	28.75	28.75	28.75	5.06	81.21	5.83	kg
[E7818] Nitrogen (water)	Output	253.59	253.59	253.59	44.6	764.03	29.18	kg
[E7885] Phosphorus (water)	Output	65.1	65.1	65.1	11.47	183.89	13.2	kg
[E9408] Water	Output	90000	90000	90000	61152.03	261128.62	61791.59	m ³

Again, it is clear that cycles can produce significantly different emissions. Particularly 03.A.01 has clearly higher eutrophication-related emissions – however, this may relate to the fact that emissions were based on total output, which was lower than the input due to the aforementioned rat infestation, potentially skewing results.

4.2. Life Cycle Inventory Results

As established, CH₄ presents one of the largest environmental concerns related to rice production. In order to better visualise its impact under the different product systems, table 14 displays the CH₄ emissions producing 100kg (equivalent) of product. The full inventory table can be found in SM C, where the individual flows are expressed in differing units.

Table 14
CH₄ as an Elementary Flow per Product System

Name	Category	Input/ Output	Product System ID	Value	Unit
[E0194] Methane, non-fossil	Elementary flows/Emission to air/high population density	Output	01.A.01	0.00049	kg
			01.A.02	0.00135	
			01.B.01	0.00108	
			02.A.01	0.00263	
			03.A.01	0.0002	
			04.A.01	0.00178	
RP Average				0.001255	kg
[E0194] Methane, non-fossil	Elementary flows/Emission to air/high population density	Output	05.A.01	0.05699	kg
			05.A.02	0.04223	
			05.B.01	0.0345	
			05.B.02	0.02025	
			05.C.01	0.02847	
Monoculture Average				0.036488	kg

Note. With a FU of 100kg equivalent

The overall emissions for monoculture are significantly higher than those for RP. While this table shows that the CH₄ emissions differ considerably between the two systems, it does not reveal how the systems perform overall, or whether these emissions are the most impactful. As direct comparison across flows will not be meaningful, and no substantive conclusions can be drawn from these values alone, the next chapters will provide a more holistic view of the systems' performances.

4.3. Life Cycle Impact Assessment

4.3.1. Characterisation Results

For the characterisation results I aggregated ICs quantitatively by multiplying them with a characterisation factor, creating the indicator result (see SM E for the aggregated result across ICs). It must be noted that differences remain between category indicators in magnitude and units, meaning that they still cannot be compared across categories: for instance, Climate Change is expressed in kg CO₂ -Eq while Acidification is expressed in mol H⁺ -Eq. Table 15 shows the category indicator results for each RP Product System.

Table 15

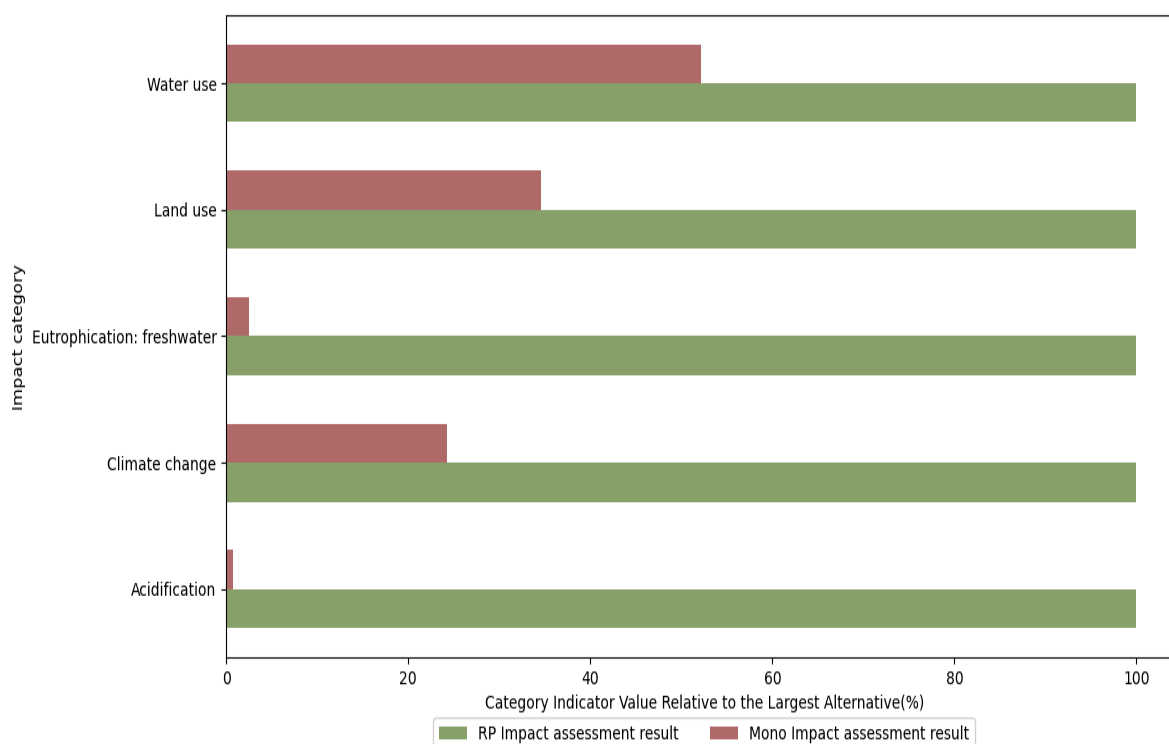
Category Indicator Result for Rice-Prawn Systems

Impact category	Acidification (mol H ⁺ -Eq)	Climate Change (kg CO ₂ -Eq)	Eutrophication : freshwater (kg P-Eq)	Land Use (dimensionless)	Water Use (m ³ world Eq deprived)
01.A.01	64.54	1831.34	6.47	12574.94	126.10
01.A.02	140.25	4708.67	23.25	23992.52	390.09
01.B.01	131.75	3655.33	2.84	30551.21	294.09
02.A.01	181.12	6056.81	3.14	27642.89	504.61
03.A.01	636.35	9287.33	86.20	74420.26	399.19
04.A.01	203.13	6956.48	3.33	38505.76	576.96

Note. Excluding 03.A.01

Thus, Figure 15 provides a relative comparison of monoculture and co-culture, with the results being averaged, where the alternative with the highest impact is represented as 100%.

Figure 15
Characterisation Results



Note. Under Impact Family EF v3.0, scaled relative to the maximum value within each IC, results aggregated across RP farms, and monoculture farms

RP systems clearly show the highest impact across all categories. For an intra-system comparison: see SM E figure 1 for the disaggregated characterisation results that reveal the RP results per product system (per cycle per field) across all ICs, and figure 2 for the results for the monoculture product systems. The normalisation result (found by dividing the indicator results with the normalisation reference for each IC) graphs can be found in Appendix J.

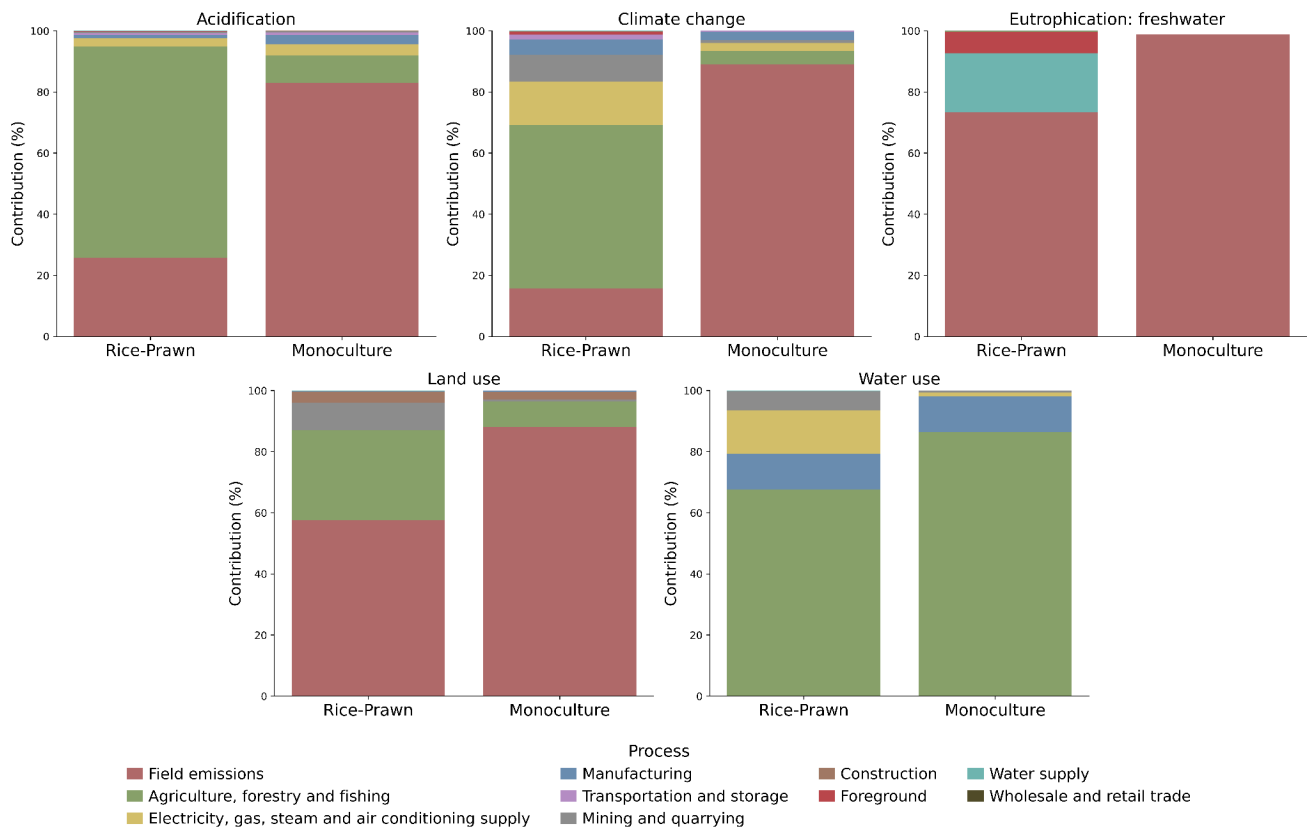
4.3.2. Contribution Analysis

Two forms of contribution analyses were chosen for this study. Firstly, direct process contributions to IC indicator results, secondly, direct environmental flow contributions to IC indicator results. This method aims to establish the contribution to overall results of various identifiable elements and parameters.

4.3.2.1. Direct Process Contribution

Figure 16

The Mean Process Contributions for the Averaged Monoculture and RP Dataset



Note. Monoculture rice farming and RP farming processes are identified in the same colour as “Field emissions” for direct comparison

Figure 16 shows that, across all ICs considered, the actual farming-stage processes exert a substantial influence on overall environmental impacts. Upon closer inspection, production systems, the contributions attributed to monoculture and RP farming (in maroon) originate predominantly from field-level farming operations and manure production processes. The "foreground" processes, shown in dark red, likewise contribute notably to the Eutrophication: freshwater category; closer inspection indicates that these contributions derive primarily from the hatchery and broodstock rearing stages. NPK (nitrogen phosphorus and potassium fertiliser) production and nursery processes exert a comparatively

smaller, though still discernible, influence on the Acidification category. Although pelleted prawn feed production contributes meaningfully to several ICs, these effects occur upstream and are therefore not represented within the present figure.

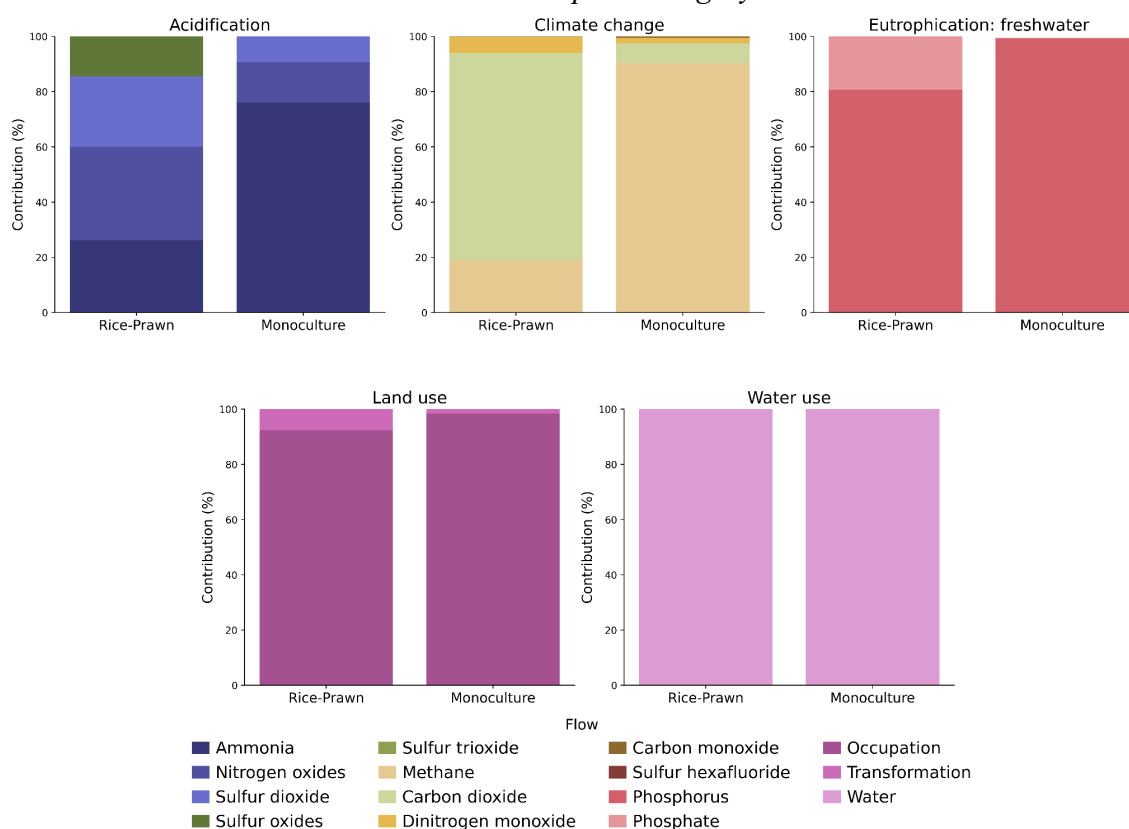
Within the Acidification IC, a major component of the contribution of agricultural processes can be attributed to diesel combustion across both systems. Indeed, agricultural processes additionally contribute substantially to Water Use, Land Use, and Climate Change across both systems. Manufacturing and electricity supply represent the next-largest contributors after agriculture, influencing Water Use, Acidification, and Climate Change, albeit to a lesser extent. It should be noted that, for figures 16 and 15, processes were aggregated at the category level, and that emissions within each category may vary considerably. Furthermore, process names have been abbreviated for clarity; full process group names are provided in SM G. This figure helps to identify the processes contributing most substantially to the impact of both systems. Thus, the following chapter examines the direct flow-level emission contributions to category indicator results, in order to help identify the specific substances and emission sources driving the impacts.

4.3.2.2. Direct Flow Contribution

The four selected ICs were maintained for the second contribution analysis, at flow level. Figure 17 displays the ICs for the environmental flow-emissions to category indicator results (see SM I and J for the full breakdown of the flow contributions).

Figure 17

Direct Environmental Flow Contributions to Impact Category Indicator Results



Note. Representing the top 10 flows that contribute to each IC, aggregated by the first word in the flow names

It is evident that many of the ICs are dominated by a few flows: Eutrophication: freshwater is dominated by phosphorus both in RP and monoculture systems. Additionally, Climate Change in the rice monoculture systems is dominated by CH₄ emissions. These results are reflected in Table 7, which found that in producing 100kg (equivalent) of product, monoculture rice plots have an output of, on average 2808% more CH₄, non-fossil, than the RP plots.

The results from the contribution analyses can be used to inform the sensitivity analysis on the most influential flows and processes. Guinée et al. (2002) described that excluded or underestimated flows that initially appear insignificant can alter results once corrected for, leading to potential false negatives. Thus, it is important to evaluate the results' robustness, especially as approaches to such analysis vary largely across the literature.

4.4. Sensitivity Analysis

I conducted three sensitivity analyses: 1) economic allocation, 2) a change in FU from 100kg to 100 USD and finally, 3) a change in FU to 1 Nutritional Density Unit. These scenarios were selected to address both methodological choices and data-related uncertainties relevant to decision-making.

4.4.1. Economic Allocation

The first sensitivity analysis will be conducted on the allocation decision for all multifunctional UPs across the product systems. The previous use of mass allocation is altered to follow economic allocation, while all other key parameters are maintained. Table 16 shows the UPs "Rice-Prawn Production" within the 01.A.01 product system.

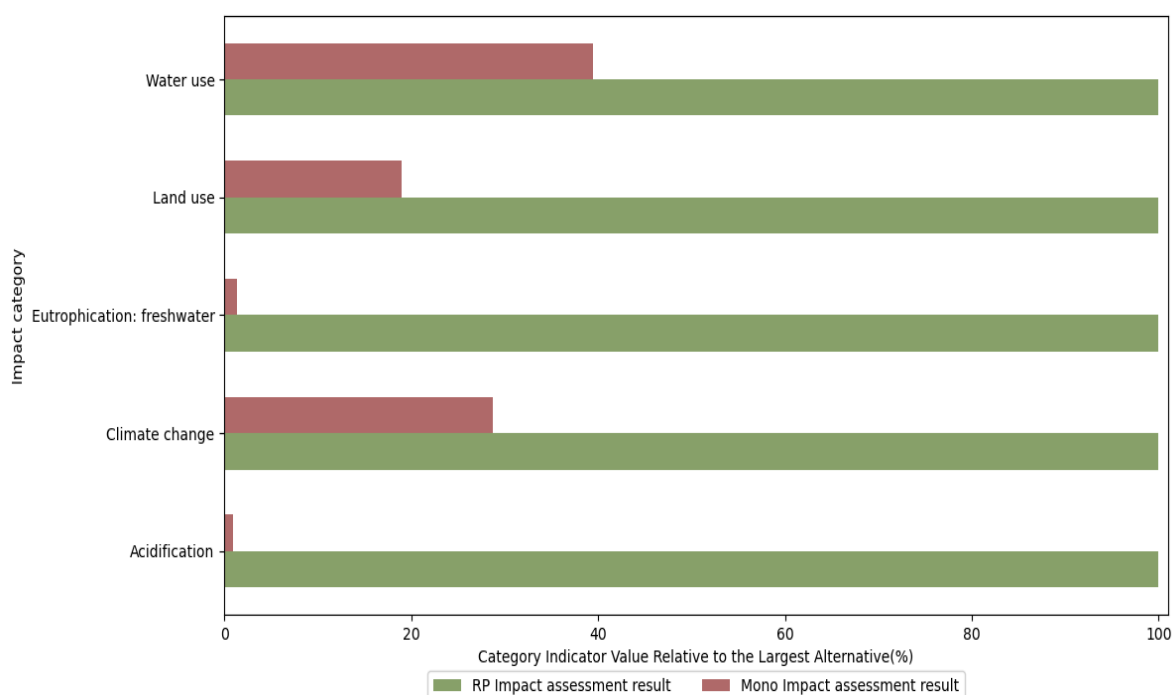
Table 16

Allocation Factors for Economic vs Physical Allocation

01.A.01 Functional flow	Physical Allocation Factor $\sum^1$	Economic Allocation Factor $\sum^1$	Revenue (USD)
Machrobachrium Rosenbergii	0.11	0.91	1770.00
Rice Prawn Paddy Rice	0.89	0.09	174.65

Note. Allocation factors for flow 01.A.01 rice prawn production

Figure 18
Characterisation Results For Economic Allocation



Note. Characterisation results for economic allocation under Impact Family EF v3.0, and functional unit 100kg, scaled relative to the maximum value within each IC, results aggregated across RP farms, and Monoculture farms. This graph is excluding the outlier of 03.A.01

Figure 18 shows that while economic allocation has a relatively small effect on the results, it consistently increases the environmental burdens attributed to the Monoculture system across all assessed ICs - notably for climate change. Despite this shift, the directionality of the comparison remains unchanged, with RP continuing to exhibit higher environmental burdens than Monoculture across all categories.

4.4.2. Market Value

The second sensitivity analysis follows the change in the reference flow to compare the alternatives based on 100 USD.

Table 17

Market Value Impact Assessment results per IC

Impact Categories	Rice Prawn Systems			Monoculture Average (100 USD)	Unit
	Prawn Average (95.61 USD)	Rice Average (4.39 USD)	Total (100 USD)		
Acidification	16.69	0.77	17.46	3.50	mol H ⁺ -Eq
Climate change	564.57	25.95	590.51	2230.11	kg CO ₂ -Eq
Eutrophication: freshwater	1.91	0.09	2.00	0.84	kg P-Eq
Land use	4380.96	201.33	4582.29	20738.49	dimensionless
Water use	52.05	2.39	54.44	335.05	m ³ world Eq deprived

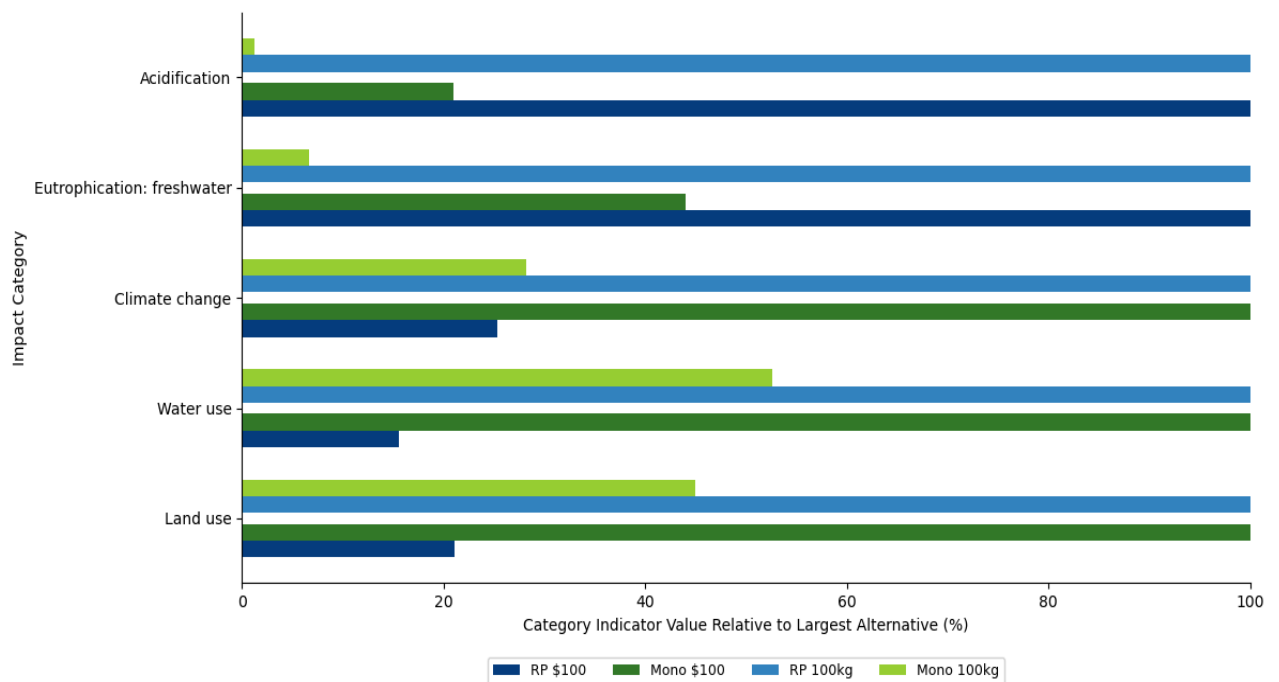
Note. Sensitivity Analysis results for both rice and prawn in the RP systems, averaged across all product systems

Table 17 shows the environmental burdens associated with each output in the RP system and monoculture system per IC. The results are averaged across all product systems. What becomes clear here is that monoculture has, on a system level, a lower environmental impact across the ICs, Acidification, and Eutrophication. However, ICs Climate Change, Land and Water Use all see RP systems performing better in terms of environmental burdens than monoculture.

Next, it is important to compare these results to the mass-based FU of 100kg in order to appropriately assess the extent this parameter change has on the results. Figure 19 shows the results of the sensitivity analysis of the MV in comparison to the mass-based functional unit of 100kg by placing each category indicator value relative to the largest alternative in percentage. The graph represents the environmental burdens for the output of prawn for the RP system.

Figure 19

The Percentage of Each Category Indicator Value Relative to the Largest Alternative for Mass vs Market Value Functional Units

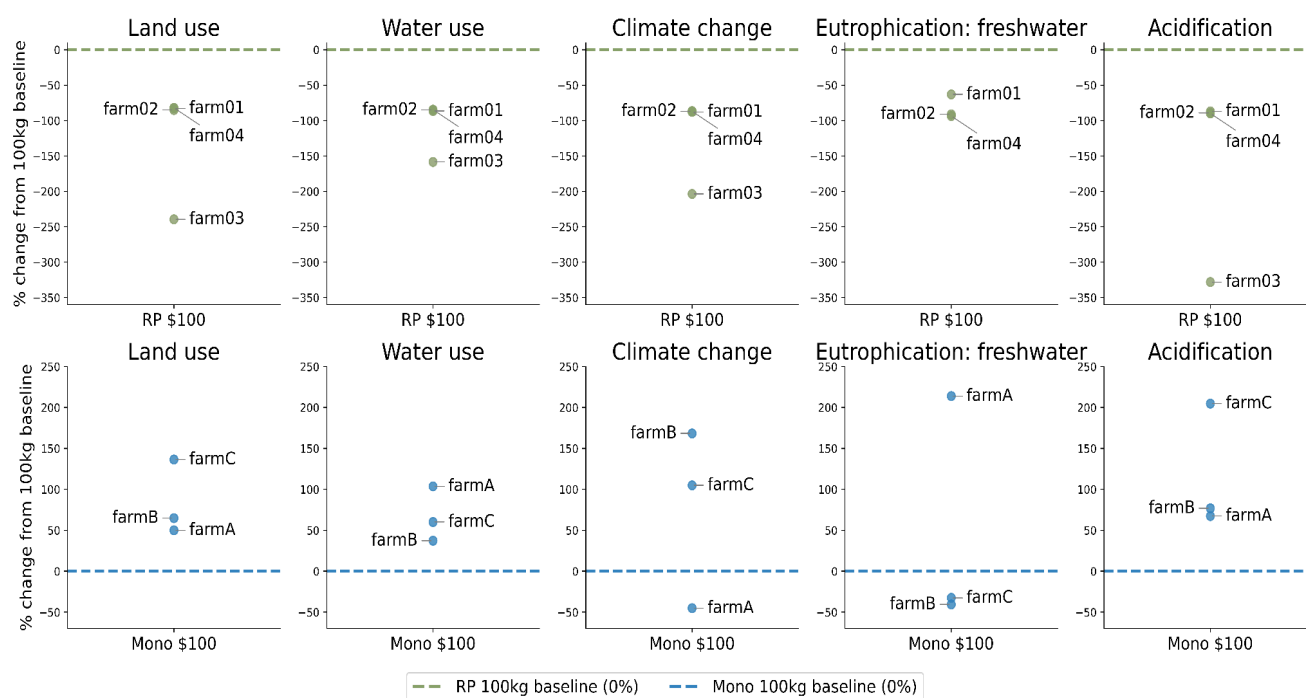


Note. The percentage of each category indicator value relative to the largest alternative for the functional unit of market value of 100 USD in comparison to the functional unit of 100 kg across the five ICs

Here it can be seen that for the ICs Acidification and Eutrophication: freshwater the RP systems maintain higher impacts in comparison to the monoculture alternatives across both functional units. However, the ICs Climate Change, Water and Land Use all experience a significant shift in results with monoculture systems representing higher environmental burdens than the RP systems. A breakdown spread of the results of the MV reference flow data is shown across the ICs in the Figure 20 below. The plots show the spread of the data in comparison to the averaged 100kg results (represented as a baseline).

Figure 20.

Percentage Change in Impact Category Indicator Results when Switching from a Mass-Based to a Market Value Functional Unit, Across Five Impact Categories



Note. The upper row shows RP results and the lower row Monoculture results, with each point representing a farm-level mean. The dashed line at 0% represents the mass-based baseline; negative values indicate a lower environmental burden under the market value functional unit and positive values a higher burden.

This figure displays the change in percentage from the averaged mass-based baseline for both Monoculture and RP product systems across the ICs. The results reveal a clear and consistent divergence between the two systems: for RP, switching from the mass-based to the economic functional unit results in a substantial decrease in environmental impact across all categories, with values falling between approximately 80% and 95% below the 100 kg baseline. For Monoculture, the opposite trend is observed, with the economic functional unit yielding an increase ranging from roughly 30% to over 100% relative to the 100 kg baseline, depending on the IC. This contrast indicates that the choice of functional unit systematically shifts the relative environmental burden between the two systems, decreasing the apparent impact of RP while increasing that of monoculture when impacts are expressed per unit of economic output rather than per unit of mass. This shift demands further research to help adequately assess whether this discrepancy holds true under different conditions.

4.4.3. Nutritional Density Unit

The third sensitivity analysis used one nutritional density unit (NDU) to consider nutritional differences between the farming systems.

Table 18

IC Results per NDU

Impact Category	Averaged Rice-Prawn	Averaged Monoculture	Unit
Acidification	0.633	0.027	mol H ⁺ -Eq per NDU
Climate change	22.354	18.240	kg CO ₂ -Eq per NDU
Eutrophication: freshwater	0.080	0.007	kg P-Eq per NDU
Land use	173.186	165.079	dimensionless per NDU
Water use	2.079	2.729	m ³ world Eq deprived per NDU

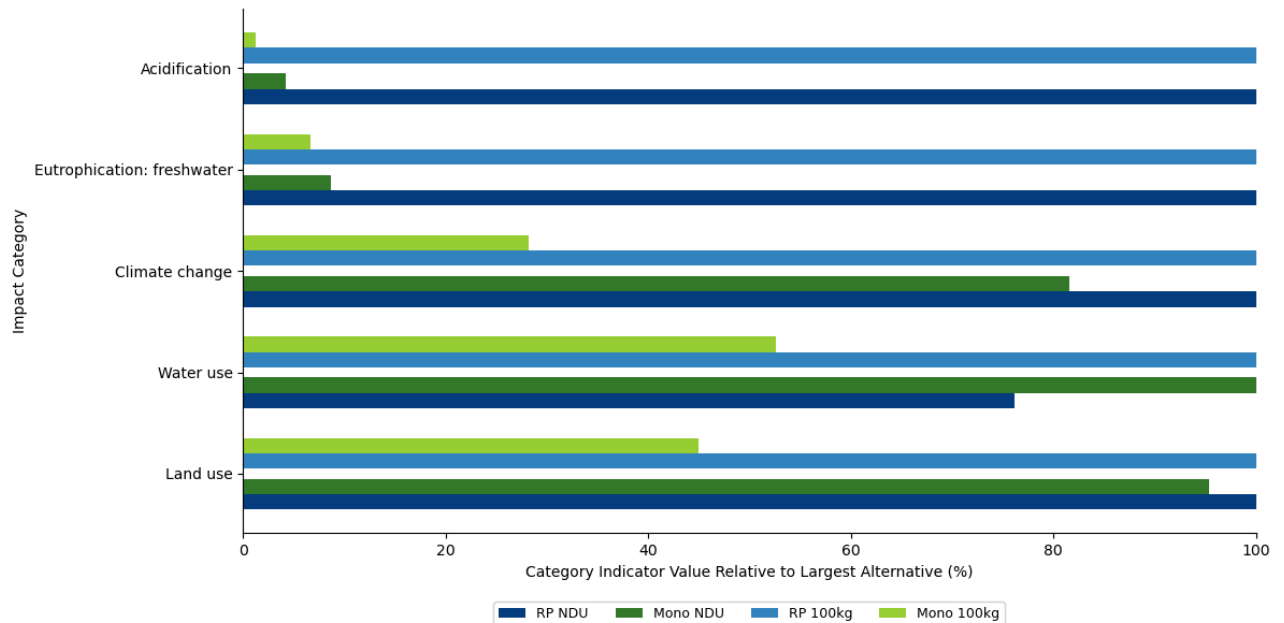
Note. Excluding outlier 03.A.01. and representing the system's nutritional density unit

It is evident that across all studied ICs the environmental burden per NDU is higher for RP in comparison to average monoculture production, apart from the IC water use. It must be noted that this result is for the entire system rather than just rice or prawn in the RP field.

To compare the change in results when altering the functional unit from 100kg to 1 NDU Figure 21 displays the percentage of each category indicator value relative to the largest alternative per FU across the ICs.

Figure 21

The Percentage of Each Category Indicator Value Relative to the Largest Alternative for Functional Unit 100kg in Comparison to Functional of 1 NDU Across the Impact Categories



The graph indicates that the relationship between RP and monoculture is broadly maintained under the sensitivity analysis using the NDU functional unit across the Acidification, Eutrophication: Freshwater, and Land Use ICs. Water use is the only IC in which monoculture exhibits a higher environmental burden than RP. Notably, however, the NDU FU reveals that the environmental impacts of Monoculture for climate change and land use are considerably closer to those of RP than was apparent under the mass-based functional unit. This suggests that the comparative advantage of RP in these categories is, to some extent, an artifact of the FU choice.

5.

Discussion

Throughout this study I assessed the environmental performance of RP co-cultures, in comparison to the more common rice monoculture systems, within the Cambodian context, following the LCA methodology. Within the context of the results, the benefits and drawbacks of such systems can be discussed.

5.1. Pros and Cons of Rice-Prawn Farming

A major advantage of RP farming is its significantly lower CH₄ emissions compared with rice monoculture, consistent with previous studies (Yang et al., 2025; Xie et al., 2011; Cui et al., 2023; Datta et al., 2009 etc.). Indeed, CH₄ emissions were seen as a dominant contributor to the environmental climate change related burdens associated with monoculture rice. Therefore, the observed reduction in CH₄ emissions within the RP system represents a potentially important environmental advantage, despite RP systems exhibiting higher burdens across other ICs. In addition, the system offers greater financial resilience for Cambodian farmers through income diversification, as also cited in literature (Phichong et al., 2025). This was demonstrated in field 03.A.01, where despite severe rice losses due to rat infestations, the farmer was still able to generate income from prawns. While RP systems generally have lower rice productivity than monocultures, they are organic, eliminating the need for synthetic fertilisers and providing opportunities to market rice at a premium price. Furthermore, prawns contribute to biological pest control by consuming local snail populations, although the impacts of this lie outside of the scope of my research.

While Yang et al. (2025) found higher rice yields in co-culture systems, this was not reflected in my studied RP systems. Indeed, lower-productivity may be expected in organic rice farming systems such as RP — which generally exhibit lower productivity compared to conventional production systems (Alvarez, 2021). The nutrient cycling benefits cited frequently in the literature (Kunda et al., 2008; Mustow, 2002; Ahmed & Garnett, 2011) did not seem to compensate in the form of higher productivity (as Xie et al. (2011) described). As both rice and prawn cultivation were accommodated in one plot, the system may make it more difficult to optimise productivity. As land use per unit of output increases, the associated burdens for the ICs closely tied to area (i.e. land use and water use) do too. Indeed, both pond evaporation and submergence-related GHG emissions, scale with surface area and lengths of cycles, both of which are higher for RP systems. Moreover, the prawns, being an animal product, require additional resource inputs compared with plant-based outputs. The additional intermediate trophic step inherently introduces inefficiencies, as a

proportion of consumed nutrients and energy is lost through metabolism, respiration and waste rather than being converted into harvestable biomass. Consequently, systems producing both plant and animal products may carry higher input requirements per unit of mass compared with systems focused solely on crop production.

5.2. Comparison between RP Systems

5.2.1. Production Cycle

Little variation in productivity was observed between production cycles within the same field, although this comparison was based on a single field with two monitored cycles. Field 01.A produced 1213 and 1135 kg ha⁻¹ in the dry and wet seasons respectively, suggesting relatively stable productivity across seasons. However, certain inputs fluctuated as expected across wet and dry, such as freshwater that required roughly half the input in the wet season. CH₄ across product systems also experienced some variation with 01.A.02 and 01.A.01 which produced almost triple the amount of CH₄: 4.90E-04kg and 1.35E-03kg respectively, under 100kg output. This is partially tied to longer harvest times for the second cycle in the wet season. Indeed, between the two cycles in 01.A all ICs saw an increase in the second cycle. For Acidification, Eutrophication: freshwater and Climate Change the higher impacts were related to higher inputs from the agriculture, forestry and fishing sector. Indeed, 01.A.02 had a significantly higher input of prawn feed, and produced more prawns and less rice in comparison to 01.A.01.

5.2.2. Fields

Productivity per hectare per cycle showed some variation between fields. Field 01.A, the first established RP field, had the highest average productivity across two cycles (1174 kg ha⁻¹), while fields 01.B.01, 02.A.01, and 04.A.01 achieved 756, 969, and 942 kg ha⁻¹, respectively. Field 03.A.01 was a clear outlier, with a substantially lower productivity of 420 kg ha⁻¹.

Field 01.A also consistently exhibited the lowest environmental impacts across all ICs (except Eutrophication: Freshwater). Acidification was significantly lower (37.9 mol H⁺ -Eq) compared to other fields, in the range of approximately 130–280 mol H⁺ -Eq. Water Use was also lowest for 01.A (132 m³ world Eq deprived), although this may partly reflect the inclusion of an additional season. A.01's Climate Change impact was 1438 kg CO₂ -Eq compared to other fields' range of 3655–9278 kg CO₂ -Eq. CH₄ emissions were highest in field 02.A (2.63 × 10⁻³ kg), followed by 04.A (1.78 × 10⁻³ kg), 01.B (9.73 × 10⁻⁴ kg), and 01.A (9.20 × 10⁻⁴ kg), while field 03.A showed substantially lower emissions (2.00 × 10⁻⁴ kg). Freshwater: Eutrophication differed within fields of farm 01, with 8.39 kg P-Eq for field 01.A and 2.84 kg P-Eq for field 01.B.

5.2.3. Farm

When averaged at the farm level, farm 01 achieved a productivity of 1,034 kg ha⁻¹ (01.B offset the higher productivity of field 01.A). Yet, productivity was relatively consistent across farms. Farm 01 also exhibited the lowest environmental impacts for acidification, climate change, land use, and water use. In contrast, farm 03 generally had the highest impacts across these categories, although it represents an outlier, partly attributable to its exceptionally low productivity and the inherent methodology's bias to total output (see the Chapter 6). Excluding farm 03, farm 01 had the highest Eutrophication: Freshwater, while farm 04 showed the highest impacts for Acidification, Climate Change, Land Use, and Water Use. Yet interestingly, CH₄ was highest from farm 02 (0.0026 kg), followed by farm 04 (0.0018kg), and farm 01 (0.0010kg) and finally farm 03 (0.0002kg).

5.3. Sensitivity Analyses

Defining the most appropriate allocation approach for systems producing two or more co-products still generates discussion. Productivity based on mass-output alone may not accurately measure environmental efficiency. Indeed, it risks implying that intensified systems are inherently more sustainable (Medeiros et al., 2017). The three different sensitivity analyses applied: allocation method, functional unit, and nutritional reference flow helped show that mass-based results were not truly robust to parameter changes.

While economic allocation resulted in only minor changes, slightly increasing the environmental burden attributed to monoculture across all ICs, FU selection had a far more substantial effect. Under the mass-based functional unit, RP exhibited substantially higher environmental burdens than monoculture across all five ICs. When the FU was redefined in terms of MV, however, this relationship reversed for Climate Change, Land Use, and Water Use; under the NDU FU, the gap narrowed considerably for Climate Change and Land Use, while Acidification and Eutrophication: Freshwater retained the same directionality as the mass-based results. Acidification was the only IC in which RP maintained a higher environmental burden than monoculture across all three FUs, though the magnitude narrowed progressively from mass-based to NDU to economic values. Yet, these shifts were most pronounced for Climate Change: while the mass-based FU indicates RP generates 254% greater impacts than monoculture, the NDU FU reduces this to a modest 22% higher impact for RP, and the economic FU reverses the relationship entirely, with RP exhibiting 75% lower impacts than monoculture. A similar reversal is observed for Water Use, where RP performs worse than monoculture under the mass-based FU but more favourably under both alternative FUs. Taken together, these findings demonstrate that the choice of functional unit can alter not only the magnitude but also the direction of the comparative environmental performance between the two product systems.

To some extent, these changes in environmental performance can be argued to be influenced by differences in what each FU equates to. Given that RP systems were found to require considerably more land, water, and feed inputs to generate the same mass of product, it

follows that once output is expressed per unit of economic or nutritional value rather than per kg, RP's comparative burden decreases significantly, as prawn scores substantially higher for both nutritional and economic value. Indeed, it is exactly this economic advantage that positions RP as a more attractive alternative for many smallholder farmers in Cambodia. Furthermore, given that RA systems are often promoted on the basis of their diversified income and nutritional contribution to smallholder farmers, the non-mass based FUs arguably better reflect the practical value proposition of the system, even though the mass-based comparison remains informative for understanding raw resource intensity per unit of biomass produced.

6.

Limitations

6.1. Data Availability

Several data-related limitations should also be considered when interpreting the results of this study. To begin, primary data were collected from a limited sample of RP farmers collaborating with WorldFish, located in Kampong Thom Province, central Cambodia. Although the initial objective was to collect data from 10–20 farms, this was reduced to four farms due to the smaller-than-expected number of established RP systems available for assessment. The limited sample size reduces the ability to capture the full variability of RP farming practices and environmental conditions across Cambodia. Restricted funding for field activities also reduced the number of site visits that could be conducted, limiting opportunities for direct verification of the data.

The timing of fieldwork relative to agricultural production cycles presented an additional methodological limitation. Due to time constraints the data collection was not able to encompass a full agricultural year across all systems, resulting in lack of data on seasonal variability for each production system. Only one RP cycle within the Cambodian wet season was included. This introduces uncertainty, particularly for variables that fluctuate seasonally or between production years. Seasonal variation is particularly important in Cambodia, where differences between wet and dry seasons strongly influence water availability, nutrient dynamics, crop management, aquaculture practices and more.

The monoculture farmer 05.B said they didn't need any inputs for rice in the wet season (B.02) because of the floods bringing in the nutrients needed to fertilise the field, resulting in the second cycle being theoretically 'organic' as no artificial fertiliser was added. However, this also created a limitation within the calculation of the eutrophication emissions, whose values were calculated based on the technological inputs. This meant that calculated field emissions for such situations fell outside the scope of the methodology.

6.1.1. Interviews and Language Barriers

Further uncertainty within my study resulted from the reliance on farmer interviews as a primary data source. Many farmers had limited experience with formal record keeping, and bookkeeping practices were often relatively new or managed by other actors within the value chain. In addition, some farmers had limited literacy, which potentially affected their documentation and communication of information. This issue became evident as upon the

second interview for data validation certain quantities and reports of methodological practices altered.

The interview-based approach may also have introduced inherent biases. Respondents may have unintentionally not reported certain activities or presented their practices in a more favourable manner. As I was conducting this research in correspondence with WorldFish, and organisations who help manage these farms and their practices, farmers may have felt pressure to report their practices in better light. Similarly, other interviewed commercial actors involved in the supply chain, such as the prawn nursery, may have been reluctant to disclose specific practices or operational details. The interviews were not recorded, as the language barrier limited the feasibility of cross-referencing audio recordings with the collected data. The familiarity of the translator to the farmers also led to occasional supplementation of respondents' answers with their own knowledge. While this provided useful contextual information, it may have reduced the extent to which responses directly reflected the interviewees' perspectives. Additionally, some nuances were inevitably lost in translation. Finally, as participation depended on the interviewees' willingness to engage with the study, only those actors who agreed to participate could be included, potentially limiting the representativeness of the collected data.

6.2. LCA Constraints

The static nature of LCA represents another limitation when assessing agricultural systems with dynamic ecological processes. LCA generally assigns environmental impacts to defined production cycles, meaning that inputs or management interventions occurring at a single point in time are allocated entirely to that production period. However, some agricultural practices generate effects that extend beyond a single cycle, either through long-term accumulation or delayed benefits. For example, soil fertility improvements, nutrient accumulation, or ecosystem changes resulting from repeated RP integration may not be adequately represented within a single-cycle assessment. Conversely, temporary impacts associated with establishment activities may appear disproportionately large when allocated entirely to one production cycle. Indeed RP's higher environmental burdens may be further influenced by the data sample itself rather than inherent limitations of the approach. As the implementation of RP systems remains relatively novel in the Cambodian context, many of the farms assessed are still considered to be in an experimental or transitional phase, with management practices and production efficiencies not yet fully optimized. Furthermore, several RP farmers reported challenges associated with pest pressures, particularly from rats and snakes preying on rice and prawn respectively, which may have negatively affected yields and contributed to variability in my results. Therefore, the results should be interpreted as representing the specific system boundaries and timeframes defined within this study rather than the full long-term environmental consequences of these farming systems.

Differences in input and management practices across the systems can also be argued to influence the results. The prawn feed pellets are a substantial contributor to

eutrophication-related impacts, as nutrients from uneaten feed and excretion are lost to runoff. Yet, the extent to which nutrients are recycled within the system (i.e. through the reuse of pond sediment as rice fertiliser) was not fully captured in my model due to the scope and time constraints. This may have led to an inaccurate estimate of net nutrient losses and therefore affected the eutrophication-related impacts for the RP system.

6.2.1. GHG Emission Calculations

Methodological limitations include the reliance on proxy calculations for GHG emissions, particularly CH₄, due to time and resource constraints. This introduced uncertainty, as emissions are highly dependent on site-specific factors such as water management, soil properties, climate, and organic matter inputs. Additionally, the simplified eutrophication model considered nutrient inputs relative to harvested outputs but did not account for nutrient cycling within the ecosystem. As a result, nutrient losses may have been overestimated in cases where unharvested biomass, such as 03.A.01's rice consumed by rats, remained within the local food web rather than being lost from the agricultural system.

Similarly, external nutrient inputs were not fully represented. 05.B.02 received no chemical inputs, with the farmer attributing nutrient deposition from seasonal flooding in the Tonle Sap floodplain. As these landscape-scale nutrient inputs were excluded from the model, the assessment does not fully capture nutrient cycling processes that can sustain agricultural production without direct human inputs, highlighting a broader limitation of simplified LCA approaches in agroecosystems.

6.2.2. Biodiversity

LCA's shortcomings include its inability to adequately capture biodiversity impacts. In Cambodian RP systems, invasive snails *Pomacea canaliculata* are commonly used as prawn feed, reducing reliance on external feed inputs while contributing to the management of an invasive rice pest. However, net ecological effects remain uncertain, as harvesting may incentivise their continued presence, or suppress native snail populations - something that conventional LCA methods cannot quantify. See Appendix H for a more extensive explanation of this LCA drawback and the impact of *P. canaliculata*.

6.2.3. Sensitivity Analysis

The sensitivity analysis also comes with some inherent constraints. Functional units based on economic values are sensitive to market fluctuations, meaning the magnitude of differences between systems may shift under different price conditions. The NDU functional unit similarly relies on simplified assumptions regarding edible portions and nutritional requirements, which may not fully capture dietary value. These limitations reinforce that future comparisons of integrated aqua-agriculture systems should report multiple functional units, as conclusions regarding environmental performance and system preference depend strongly on the chosen reference flow (Henriksson et al. 2015).

6.3. Recommendations

6.3.1. Co-culture Farming Techniques

Several environmental hotspots point toward concrete opportunities for improving RP performance. Intermittent drainage, paired with careful consideration of prawn water requirements, could help offset CH₄ emissions from prolonged submergence. Improving feed conversion efficiency and application timing would reduce nutrient inputs and subsequent losses, mirroring nitrogen-efficiency strategies shown to reduce N₂O emissions, NO₃⁻ (nitrate) leaching, and NH₃ volatilisation in monoculture fertiliser management (Dawson et al., 2008). More deliberate use of pond sediment as organic fertiliser for the rice crop could further improve nutrient cycling, reducing external inputs and narrowing the eutrophication gap between systems (Adhikari et al., 2014).

It should be noted, however, that RP is not the only viable mitigation strategy. You (2026) highlights that water management interventions are often constrained by inconsistent farm-level implementation, and suggests that low-emission rice varieties may offer substantial CH₄ reductions without requiring fundamental changes to farming practice. Whether the primary objective is GHG minimisation or broader livelihood and environmental goals will therefore determine the appropriateness of RP systems within any given decision-making context.

6.3.2. Methodological Improvements

Given these limitations, the findings should be interpreted as an initial comparative assessment. Future research should prioritise larger sample sizes and longitudinal monitoring across seasons and direct field measurement of GHG emissions — particularly CH₄. Lansing and Kramer (2011) identify reduced submergence duration as an effective strategy for mitigating rice-related CH₄ emissions. Additionally previous studies, such as Liu et al (2025), suggest that prawn activity may further reduce emissions through mechanisms such as sediment disturbance. However, both of these effects remain unquantified for Cambodian RP systems. The exploration of additional functional units such as water productivity, which is the net benefit per unit of water consumed, represents a particularly relevant metric for integrated farming systems in water-stressed regions such as (increasingly) Kampong Thom (Ahmed et al., 2022). Applying such a functional unit in future LCA studies of RP systems would offer a more complete picture of their resource efficiency and could strengthen the case for their adoption in water-scarce contexts. However, more exploration and comparison of different approaches is still needed. Incorporation of biodiversity indicators would further address gaps that fall outside conventional LCA scope, collectively building a more holistic evidence base for RP co-culture in Cambodia's sustainable agricultural development.

7.

Conclusion

This study provides one of the first Life Cycle Assessments of rice-prawn (RP) co-culture systems in Cambodia, comparing their environmental performance to conventional rice monoculture across a single agricultural cycle. When assessed per kilogram of output, monoculture was consistently less environmentally burdensome than RP across all five Impact Categories (Water Use, Land Use, Eutrophication: freshwater, Acidification and Climate Change). This, in part reflects RP's lower productivity (905 kg/ha versus 3,200 kg/ha), which translates into greater land, water, and input requirements per unit of output. Field-level farming operations, diesel combustion, and manure management were the dominant impact sources across both systems, with hatchery and broodstock rearing additionally driving freshwater eutrophication in RP through phosphorus losses. While small seasonal variations were evident, the sample size used within my research was too small to draw definite answers.

Furthermore, when the comparison was reframed in terms of economic or nutritional value, monoculture showed higher environmental burdens than RP for Climate Change, Land Use, and Water Use. This reversal demonstrates that the choice of how outputs are valued can fundamentally change which system appears more sustainable. Only Acidification and Freshwater Eutrophication consistently favour monoculture regardless of metric. Nevertheless, RP systems produced substantially less methane per unit of output than monoculture, a meaningful climate advantage that deserves specific attention in assessments of rice-based farming systems.

As RP farming continues to develop in Cambodia, the evidence presented here suggests that despite their higher environmental burdens, with targeted improvements to productivity and input management, integrated RP systems could hold genuine potential to simultaneously support smallholder livelihoods, reduce methane emissions from rice cultivation, and contribute to more sustainable food production — making them a worthwhile focus for continued investment, research, and policy support.

8.

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9.

Appendix

Appendix A. Research Aim and Link to Industrial Ecology

Through this project I aimed to support Cambodian farmers and policymakers by providing evidence for more sustainable, lower-input farming systems that improve resilience and decrease environmental burdens. As no LCA-based research exists on RP systems in this context, my thesis presents novel empirical data and is essentially the first LCA of such RP integrated systems, contributing to the scientific understanding of sustainable aquaculture and circular nutrient systems. The project directly aligns with the MSc Industrial Ecology's focus on sustainability assessment, food system transitions, and quantitative environmental modelling.

Contribution to the Research Problem

By following this structured research approach, each method directly contributes to answering its associated sub-research point, and together work to answer the main research question. As almost no LCA-based studies exist for RP co-culture systems globally, this work provides the first empirical LCA of Cambodian systems. The results of my research aim to support both Cambodian farmers and policymakers by offering evidence-based insights into low-input, climate-resilient agricultural strategies. The research therefore fills a significant scientific gap while contributing actionable knowledge to co-cultures and sustainability.

Appendix B. Research Design and Logic

My overall research design followed a mixed-method, sequential approach in which primary data collected from farms in Cambodia formed the foundation for LCA inventory compilation and subsequent impact assessment. The research aligned with ISO 14040/44, depicted in Figure 3, which divides LCA studies into four methodological phases: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation. It should be acknowledged that LCAs, as a methodology, were developed primarily for industrial systems, where inputs, outputs, and system boundaries are relatively well-defined and consistent. Applying it to smallholder agricultural systems such as RP

co-culture introduces inherent limitations, as these systems are characterised by high spatial and temporal variability, informal practices, and ecological interdependencies that do not translate neatly into the standardised LCA framework. As such, the results of this assessment should be interpreted with the understanding that LCA is not fully optimised for this context. Therefore, while LCA is an important and useful tool to assess comparisons in environmental performance, the nuances inherent to these farming systems will not be fully captured by the methodology. Nevertheless, the different phases are outlined below.

Phase 1: Goal and scope

In Phase 1, the goal and scope of the LCA are defined. This is the first official step of LCA modelling aligned with ISO 14040/44. Thus, through discussions with WorldFish Cambodia and academic supervisors, and supported by existing WorldFish datasets, appropriate system boundaries, and a functional unit can be defined. Here, my presence in the field begins as this will help to narrow the research field. This step ensures that functionally comparable systems are assessed and that my LCA scope will be able to adequately address the core research objective. Thus, this stage directly supports the first sub-research question.

Phase 2 Life Cycle Inventory Analysis

In this phase, the compiled inventories are calculated to understand comparative environmental life cycle impact assessment. With the completion of this chapter the first sub-research question can be adequately answered in order to determine what the most relevant inputs and outputs that characterise the life cycles of integrated RP co-culture systems and the monoculture reference system of rice are.

Phase 3: Life Cycle Impact Assessment

The LCIA converts LCI data into environmental impact results by applying characterisation factors and impact models. Environmental Footprint (EF v3.0) will be used as the primary LCIA method due to its comprehensive midpoint coverage.

In characterisation, each classified flow is multiplied by its associated characterisation factor to convert it into a common impact indicator unit (e.g., kg CO₂-eq for climate change or kg PO₄³⁻-eq for eutrophication). This allows flows of different substances and magnitudes to be aggregated within each IC. The resulting midpoint indicators provide a quantitative basis for comparing integrated and non-integrated production systems. This step addresses sub-questions related to the environmental performance of each system and the identification of major drivers of impacts

The outcome of this phase will be a comparative environmental impact profile of integrated RP systems versus separate rice monocultures - directly answering the second sub-research question.

Classification

During classification, each elementary flow from the inventory is assigned to one or more ICs. For example, CH₄ emissions from flooded fields contribute to climate change, while nitrogen leaching contributes to eutrophication. As some flows influence multiple environmental mechanisms, they may be assigned to several categories. This step is performed automatically within the openLCA software using the embedded category-flow links defined by EF and ReCiPe. As a result, each flow is directed to the appropriate ICs prior to characterisation, ensuring that substances with, for instance, serial impact pathways, are correctly represented.

Characterisation, Lacking factors, and Normalisation

Characterisation aggregates the classified ICs quantitatively by multiplying them with a characterisation factor, thereby creating the indicator result. There are, however, interventions for which characterisation factors are lacking which will ultimately impact the results, thus these will be specifically outlined for clarity.

Normalization, on the other hand, helps to clarify the relative magnitude and importance of category indicator results. Normalizing results describes dividing the indicator results with the normalisation reference for each IC. This step supports the interpretation through highlighting which impacts are the greatest. This should reveal potential inconsistencies, and prepare results for subsequent procedures.

Economic flows not followed to system boundary

Certain lifecycle stages, such as additional packaging in intermediate exchanges, chemicals, facility infrastructure, by-products and excess-products, and manufacturing requirements are not all fully accounted for. This is especially pertinent in countries such as Cambodia where datasets such as in Ecoinvent are distinctly lacking. Indeed, there are data (and scope) gaps which prevent the specification of several flows, leading to estimates or cut-offs. This will unequivocally affect the reported impact results, however, this is likely to cause only minor differences to the final conclusions as these will be consistent across the alternatives assessed.

Phase 4: Interpretation, Contribution, and Sensitivity Analysis

Phase 4 uses the LCIA results to identify environmental hotspots, trade-offs, and uncertainties. Contribution analysis is used to determine which life cycle stages and processes contribute most significantly to impacts in each system. The completeness checks will test the consistency of my data, and ensure the results follow logically. Next, the sensitivity analyses will be conducted to test the robustness of results to the variations in key parameters, and also between the methodological choices (EF versus ReCiPe). This will address the hotspots and the sensitivity of my model.

Appendix C. WorldFish Research Framework

The four small-holder RP farmers included in my research were selected from those already participating in an ongoing WorldFish project to establish RP farming in Kampong Thom Province. These farmers were selected by WorldFish based on specific criteria, including their willingness to adopt RP farming, access to water and initial capital, availability of labour, and ability to source local supplementary feed, as well as their readiness to learn and cooperate with technical support (WorldFish, 2026). This project forms a part of the ASEAN-CGIAR Intervention Package, which promotes regenerative agriculture and circular economy principles through an integrated rice - freshwater prawn (- vegetable) farming system. It aimed at improving farm productivity, diversifying income, and enhancing environmental sustainability under local agroecological conditions. It was conducted from December 2024 to November 2025 in Kampong Thom Province in Cambodia. WorldFish sponsored and supported the implementation of solar-powered pump irrigation, monitored freshwater prawns' growth rates and yields, assessed rice variety performance, and carried out an economic analysis of the system. These locations are as WorldFish supported the establishment of the RP techniques within the farms with the intention of fostering a collaborative community of RP farmers able to share materials, knowledge, and technical practices. Similarly, the monoculture rice farms were also located within Kampong Thom province, often in adjacent plots to the RP plots. The first cycle of the experiment was fully supported by the project from December 2024 to June 2025. Funding for the second cycle from June to December 2025 was covered by the farmer with additional technical support from WorldFish.

Appendix D. Table of Involved Parties

Table 18

Table of Involved Parties

Role	Person	Affiliation
Steering committee, commissioners and expert reviewers	Patrik Henriksson	Leiden University
	Linda Kamp	
Research Commissioners	Ou Phichong	WorldFish Cambodia
	Sun Vathanak	
	Sean Austin	
Researcher	Aline Mellersh	Leiden University & Delft University of Technology

A) Farmer: 01

Located in Kor-Koh village, this is the only farm that, at the time of the first interview, had completed two agricultural cycles - one full agricultural year. Farmer 01 started her first RP agricultural cycle in December 2024. She runs the farm alongside her husband and another family member. Two fields are dedicated to RP farming which is 14% of her total farmland. The stocking ditches for the two RP plots are both U-shaped. She started with rice variety 5154, but quickly transitioned to Tubtim Chum Phae (see SM A table 4 for further breakdown of nutritional differences between rice varieties). She continues to stock *M. Rosenbergii*.

B) Farmer: 02

Also located in Kor-Koh village, farmer 02's RP plot takes up 24% of her total farmland. Like farmer 01, she also has a U-shaped prawn stocking ditch around the rice paddy. She plans on expanding to two more RP fields in the future. She started her first agricultural RP cycle in September 2025, and the full agricultural year will be completed in September 2026. Farmer 02 runs the farm with her husband. She stocks rice variety Tubtim Chum Phae, and M. Rosenbergii.

C) Farmer: 03

Farmer 03 currently has one RP plot. This takes up 55% of his farmland. He plans on expanding into two more plots for his RP farm. He started his first RP agricultural cycle in August 2025 and will likely end his first agricultural year in December 2026. His stocking ditch is also U-shaped. He started farming the rice variety Phka Rumduol but switched over to Rieng Chey after his first harvest.

D) Farmer: 04

Farmer 04 currently has one RP plot which takes up 27.3% of her farmland. She started her first RP agricultural cycle in September 2025. She could not complete a full agricultural cycle as her access to her water source was cut-off (the local water authorities were fixing the water gauge upstream) before she began her second cycle. She did, however, fall back to monoculture rice during this water shortage in her RP plot. Her stocking ditch is also U-shaped. She started farming 5154 rice variety in the RP plot.

Farmer 04 also farms one monoculture rice plot (05.A). This takes up 45.4% of her farmland, the rest consisting of a RP plot and a catfish-rice plot, and some vegetable plots. She started monoculture rice farming over 40 years ago. She typically farms Rumdoul variety and Tibitim Chumphae over one agricultural year, harvesting twice in this time.

E) Farmer: 05.B

Farmer 05.B currently owns one monoculture rice plot. This takes up 33.33% of his farmland, the rest consisting of 2 hectares of cashew plantations. He has completed over 45 years of farming, and has been farming in the studied plot for 35 years. He typically harvests twice in one year, farming Rumdoul variety for the first cycle and 5154 for the second.

F) General Data (05.C)

The final monoculture plot was modelled after common rice monoculture farming practices in Cambodia. Data for this were modelled after descriptions taken from both farmers 05.B and 05.A on common practices of monoculture farmers in Kampong Thom. Other data were sourced from an internal dataset from WorldFish Cambodia.

Appendix E. Survey for Agricultural production for RP

Survey for Agricultural production for RP (LCA)

1. Survey and Interview details

This questionnaire is part of an MSc thesis in Industrial Ecology within the joint programme of Leiden University and Delft University of Technology, conducted by Aline Mellersh. The survey aims to gather information on feed supply for prawn-rice co-culture farming in Cambodia. This information will support a Life Cycle Assessment (LCA), which is used to evaluate the environmental impacts of this farming system and compare it with more traditional monoculture farming approaches.

1.1 Survey details.

Farm Name	Farm Number	Date

1.2. Farm Location

District	Town/Village	Farm Address	Short Description

1.2.1. What3Words (if necessary)

1.	2.	3.
----	----	----

1.4. Respondent, manager and owner details (identification letter used throughout survey)

Respondent(s)	Full Name	Farm Role	Tel. Number
A			
B			
C			

D			
---	--	--	--

1.5 Labour

	No.	Avg. h/day	Days/yr	Total cost	Unit	Other benefits
Family members						
Full-time labour						
Part-time labour						

2. General information

2.1. Reference period, this should be used as the time frame for all following questions

	Wet Season	Dry Season
When did you start your first ever Rice-Prawn production cycle?		
When did you last fully complete the Rice-Prawn production cycle?		

When did/do you (expect to) complete the first agricultural year?		
Is the length of the production cycle different in the wet vs dry season?		

Planting and harvest patterns

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2.2. Profile of holding

Site area (m^2)	
Production/harvested area (m^2)	
Depth of pond (cm)	
Other areas for production (m^2)	
Rent paid (local currency)	

Period covered (months)	
Land-lease length	
Extra Notes/ visuals	

3. Operational details: RICE

3.1. **Type of crop(s) and yield (all crops and cycles)** Recurring IDs for the next few tables:

ID	Type of crop (hybrid, local, etc)	Production Cycle Period	Production area	Total yield all harvests (kg)	Value per unit (USD/riel)	Is field flooded prior to cultivation and how long? (days)
1						

2						
3						

3.1.1 DRY: Type of crop(s) and yield

ID	Total Yield DRY season/C ycle	Value per unit DRY (USD)	Time of plantatio n	Time of harvest	Is field flooded prior to cultivation and how long? (days)	Water regime e.g irrigated, flooded, etc.	Notes
1							
2							
3							

3.1.2 WET: Type of crop(s) and yield

ID	Total Yield WET season/C ycle	Value per unit WET (USD/rie l)	Time of plantati on	Time of harvest	Is field flooded prior to cultivation and how long? (days)	Water regime e.g irrigated, flooded, etc.	Notes
1							

2							
3							

3.2. Seed origin, cost of seeds and amount of seed per cycle (continue ID from previous question):

ID	Origin*	Cost per kg Wet (USD/kg)	Amount of seed Wet cycle (kg)	Cost per kg DRY (IUSD/kg)	Amount of seed DRY cycle (kg)
1					
2					
3					
4					
5					
6					

***L.** saved from previous harvest; **M.** From neighbor / friend; **N.** From relative; **O.** From input shop; **P.** Other (specify

4. Operational details: PRAWN

4.1. Prawn ORIGIN (POST LARVAE), cost and amount per cycle (continue this ID to next questions):

ID	Species	Origin*	Cost per kg Wet (USD/kg or heads)	Amount of prawn Wet cycle (kg or heads)	Cost per kg Dry (USD/kg or heads)	Amount of prawn Dry cycle (kg or heads)
1						
2						
3						

***L.** saved from previous harvest; **M.** From neighbor / friend; **N.** From relative; **O.** From input shop; **P.** Other (specify)

4.2 Grow Out Cycles

4.2.1. Stage 1, last complete cycle: _____

ID	Amount stocked (heads or Kg)	Time of planta tion	Surviv al rate (%)	Time of harvest	Amount Harvested (heads or Kg)	Average Market price (USD)	Feed ID	Other inputs (e.g. oxygen)
1								
2								
3								

4.2.2 Stage 2, last complete cycle: _____

I D	Amount stocked (heads or Kg)	Time of planta tion	Surviv al rate (%)	Time of harvest	Amount Harvested (heads or Kg)	Average market price	Feed ID	Other inputs (e.g. oxygen)
1								
2								
3								

4.3 Type of feed (i.e. pelleted feed, natural feed, etc.)

ID	Type of feeds	Origin/Brand	Total Unit	Notes
E				
F				
G				
H				
I				

4.3.1. Content of Feed

Fillers	E		F		G		H		I		Total use	
	Unit	Cost	Unit	Cost	Unit	Cost	Unit	Cost	Unit	Cost	Unit	Cost
Rice/broken rice												
Rice bran												
Rice hulls												
Wheat flour												
Maize bran												
Corn gluten feed												
Corn gluten meal												
Snail feed												

--	--	--	--	--	--	--	--	--	--	--	--	--

5. Fertilizers and pesticides

5.1 Inorganic fertilizers

I D	Fertilizer name	N (%)	P (%)	K (%)	Quantity	Cost (US D)	Time of application WET	Time of application DRY
1								
2								
3								
4								
5								
6								

5.2 Organic Fertilizers

I D	Manure from	Quantit y	Cost (USD)	Time of application WET	Time of application DRY	Notes
1						

I D	Manure from	Quantity	Cost (USD)	Time of application WET	Time of application DRY	Notes
2						
3						
4						
5						
6						

6. Pesticides and alkalines

6.1 Pesticides

Pesticide type	Quantity	Cost	Time of application WET	Time of application DRY	Notes
1.					
2.					
3.					
4.					

6.2 Alkaline (e.g. limestone or quicklime)

Type	Quantity	Cost	Time of application WET	Time of application DRY	Notes
1.Quick Lime					
2. Dolomite Powder					
3.					
4.					

7. Water resources

7.1 Water source and Storage

	Description	Unit WET	Cost*	Unit DRY	Cost*
Main water source					
Distance to Main Source if Pumped (km)					
Secondary water source					
Water usage					
Water Storage Method					

Main water discharge to					
-------------------------	--	--	--	--	--

*if municipal

8. Energy

8.1 Main energy sources.

Energy Source last cycle	Total consumption first cycle		Total consumption second cycle		Total
	source	unit	source	unit	
Grid electricity (kWh)					
Propane/LPG (liter)					
Gasoline (liter)					
Diesel (liter)					
Coal (kg)					
Wood (kg)					
Solar Panel (kWh)					

8.2 Energy consumption

Main energy use by cost, percentage/rank

Consumption	Electricity	Propane/LPG	Petrol/Diesel	Solar
Generators				
Pumping				
Farm vehicles				
Water storage tank				

Appendix F. Survey for Feed Supplier for Prawn

Feed Supplier for Prawn (LCA)

Objective of the Questionnaire:

This questionnaire is part of an MSc thesis in Industrial Ecology within the joint programme of Leiden University and Delft University of Technology, conducted by Aline Mellersh. The survey aims to gather information on feed supply for prawn-rice co-culture farming in Cambodia. This information will support a Life Cycle Assessment (LCA), which is used to evaluate the environmental impacts of this farming system and compare it with more traditional monoculture farming approaches. By understanding feed sourcing, production, and distribution, the study can develop a more complete picture of the farming process and its potential environmental benefits.

1. Survey and Interview details

1.1 Survey details.

Supplier Name	Supplier Number	Date

1.2. Supplier Location

District	Town/Village	Supplier Address	Short Description

1.2.1. What3Words (if necessary)

1.	2.	3.
----	----	----

1.3. Respondent, manager and owner details (identification letter used throughout survey)

Respondent (s)	Full Name	Supplier Role	Tel. Number
A			
B			

C			
D			

1.4. Labour

	No.	Avg. h/day	Days/yr	Total cost	Unit	Other benefits
Owner						
Full-time labour						
Part-time labour						
Family members						

1.5 Have you (& other employees) followed any training in feed processing?

Training	Year	From whom*

*1=friend; 2=relative; 3=other feed processors; 4=Government technician / extension officer;
5=private sector technician; 5=self-learned; 6=other (specify)

2. General information

2.1. Profile of holding

Year Established	
Type of ownership*	
Site area (m^2)	
Fish processing area (%)	
Extra Notes/ visuals	

*1=state owned company; 2=equitised (shareholders); 3=registered private foreign; 4=joint venture; 5=registered private national; 6=non-registered private national; 7=non-registered private foreign; 8=cooperative; 9= other (specify)

2.2 What activities does this supplier do?

	Tick if yes	Please rank the activities based on its priority (1 = main priority)	Amount of sales revenue from this activity (local currency/year)
Produce complete feed			
Produce concentrate feed			
Produce raw materials			
Sell raw material inputs			
Buy and sell feed (as agent/trader)			
Produce livestock from own farms			
Produce livestock from contract farms			
Produce prawn from own farms			
Produce prawn from contract farms			
Other (specify)			
Other (specify)			

2.3 Type of feed (i.e. pelleted feed, natural feed, etc.)

I D	Type of feeds	Origin/Brand	Total Unit Produced	Total Unit Sold	Shelf life	Notes
E						
F						
G						
H						
I						
J						
K						
L						
M						

2.4 Price per Bag

Feed ID	Price per bag (USD OR riel /unit)	Notes

Notes

--

2.4.1 Content of Feed

		E			F			G			H			I		
		Unit	Origin	Cost	Unit	Origin	Cost	Unit	Origin	Cost	Unit	Origin	Cost	Unit	Origin	Cost
Fillers	Rice/broken rice															
	Rice bran															
	Rice hulls															
	Wheat flour															
	Maize bran															

	Corn gluten feed															
	Corn gluten meal															
Protei n Rich	Snail feed															
	Meat & bone meal															
	Soybe an meal															
	Groun dnut cake															

3. Demand

3.1. Demand Fluctuations per season

Year	Season	Units Produced	Units Sold (USD or Riel /kg)	Fluctuation Description

4. Water resources

4.1 Water source and Storage

	Description	Unit used	Cost*(USD or Riel /kg)
Main water source			
Distance to Main Source if Pumped (km)			
Secondary water source			
Water usage			
Water Storage Method			
Main water discharge to			

*if municipal

5. Energy

5.1 Main energy sources.

Energy Source last cycle	Total consumption first		Total consumption second		Total
	source	unit	source	unit	
Grid electricity (kWh)					
Propane/LPG (liter)					
Gasoline (liter)					
Diesel (liter)					

Coal (kg)					
Wood (kg)					
Solar Panel (kWh)					

5.2 Energy consumption

Main energy use by cost, percentage/rank

Consumption	Electricity	Propane/LPG	Petrol/Diesel	Solar
Generators				
Pumping				
Mechanical vehicles				
Water storage tank				

Appendix G. Survey for Prawn Hatchery

Prawn Hatchery (LCA)

Objective of the Questionnaire:

This questionnaire is part of an MSc thesis in Industrial Ecology within the joint programme of Leiden University and Delft University of Technology, conducted by Aline Mellersh. The survey aims to gather information on feed supply for prawn-rice co-culture farming in Cambodia. This information will support a Life Cycle Assessment (LCA), which is used to evaluate the environmental impacts of this farming system and compare it with more traditional monoculture farming approaches. By understanding prawn hatchery sourcing, production, and distribution, the study can develop a more complete picture of the farming process and its potential environmental benefits.

1. Survey and Interview details

These questions are specifically regarding the Macrobrachium Rosenbergii

1.1 Survey details.

Hatchery Name	Date

1.2. Hatchery Location

District	Town/Village	Address	Short Description
Kandal stung, Kandal Province			

1.3. Respondent, manager and owner details

Full Name	Job Role	Tel. Number (optional)

2. General information

2.1. Profile of holding

Year Established	
Total Site area (m^2)	
Total area of Hatchery for Macrobrachium Rosenbergii (m^2)	
Number of production cycles in a year for Macrobrachium Rosenbergii	
Number of Macrobrachium Rosenbergii hatchery ponds	
Plans to expand hatchery? (# of ponds and m^2)	
Number of Macrobrachium Rosenbergii nursery ponds	1)
Plans to expand the nursery? (# of ponds and m^2)	
Average weight of prawn when sold (kg)	
Extra Notes/ visuals	

3. Nursery Ponds

3.1 What is the stocking density, size, and depth of each pond?

	Nursery ponds				
	A	B	C	D	E
Size of each pond (m^2)					
Depth of each pond (cm)					
Stocking Density per container					
Gender of PL (Male/female or both)					
Equipment in the pond (pump, nets etc.)					

3.2. Pond A - stage 1)

Cycle	Date Stocked (dd/mm/y)	Amount Stocked (& average weight) (PL)	Survival rate (%)	Date Harvested (dd/mm/y)	Amount Harvested (& average weight) (kg)	Holding facility (e.g. cement tanks)	Origin of PL	Inputs (e.g. Antibiotics, Water conditioners, fertilisers etc.)
1								
2								

3								
---	--	--	--	--	--	--	--	--

3.3. Pond B - 2 stage)

Cycle	Date Stocked (dd/mm/y)	Amount Stocked (& average weight) (kg)	Survival rate (%)	Date Harvested (dd/mm/y)	Amount Harvested (& average weight) (kg)	Holding facility (e.g. cement tanks)	Origin of PL	Inputs (e.g. Antibiotics, Water conditioners, fertilisers etc.)
1								
2								
3								

4. Hatchery Ponds

4.1 What is the stocking density, size, and depth of each pond?

	Hatchery ponds				
	F	G	H	I	J
Size of each pond (m^2)					
Depth of each pond (cm)					
Stocking Density per pond					
Gender of PL (Male/female or both)					

Equipment in the pond (pump, nets etc.)					
---	--	--	--	--	--

4.2. Pond F

Cycle	Date Stocked (dd/mm/y y)	Amount Stocked (& average weight) (kg)	Survival rate (%)	Date Harvested (dd/mm/y y)	Amount Harvested (& average weight) (kg)	Holding facility (e.g. cement tanks)	Origin of PL	Inputs (e.g. Antibiotics, Water conditioners, fertilisers etc.)
1								
2								
3								

4.3. Pond G

Cycle	Date Stocked (dd/mm/yy)	Amount Stocked (kg)	Survival rate (%)	Date Harvested (dd/mm/yy)	Amount Harvested (kg)	Holding facility (e.g. cement tanks)	Origin of PL	Inputs (e.g. Antibiotics, Water conditioners, fertilisers etc.)
1								
2								
3								

5. Broodstock management

Note: Please skip Q. 5 if operator doesn't rear their own prawn brood

5.1 Information on farm-reared broodstock

Origin (Company and country)	Transportation (e.g. truck, plane, train)	Total amount purchased per grow out season	Pond size (m ²)	Sex (M/F)	Price paid (riel or USD / kg)

6. Feed

6.1. Used for Hatchery, Nursery, Broodstock

Brand or Item	Quantity total (purchased per cycle) (kg)	Cost	Unit
Pelleted feed - apsara	1 month broodstock -> 1 bag		

6.2 Commercial feed or homemade feed inputs

Brand/ item	Origin	Quantity Purchased (kg)			Cost (riel or Dollar)
		For one cycle			
		Broodstock	Nursery	Hatchery	
Golden apple snail					
Pelleted					
Post larvae stage - 50 cans - 425 g /can					

7. Therapeutics and feed supplements, quicklime, dolomite, limestone etc.

Substance Type	Use (which pond?)	Amount per application	Time of application	Total purchased per cycle	Total Cost

8. Water resources

8.1 Water source and Storage

	Description	Unit used annually	Cost*(USD or Riel / Liter)
Aqueduct			
Main water source			
Distance to Main Source if Pumped (km)			
Secondary water source			
Water Storage Method			
Main water discharge to			

*if municipal

9. Energy

9.1 Main energy sources used for one cycle

Energy Source	Total consumption first		Total consumption second		Total
	source	unit	source	unit	
Grid electricity (kWh)					
Propane/LPG (liter)					
Gasoline (liter)					

Diesel (liter)					
Solar Panel (kWh)					

9.2 Energy consumption

Main energy use by cost, percentage/rank

Consumption	Electricity	Propane/LPG	Petrol/Diesel	Solar
Generators				
Pumping				
Mechanical vehicles				
Water storage tank				

Appendix H. LCA and Biodiversity

A weakness of LCAs is the issue of accurately representing biodiversity benefits or drawbacks. For example, the feed inputs for the prawns are Golden Apple Snails (*Pomacea canaliculata*), an invasive species which were first discovered in the wild in Cambodia in 1995 (Saito et al., 2025). They were purposefully introduced for human consumption due to their high protein content. However, they quickly became a rice pest, and since then, this invasive species quickly spread to many provinces, including Kampong Thom (Saito et al., 2025). Golden Apple Snails are a main food source used for the Giant River Prawns, as they are abundant and high in protein. The collection of the snails also works as a small income for many local children who will collect the snails and sell them to the farmers. Golden Apple Snails are especially common as a feed source as they are distinctly unpopular within Cambodia for local consumption, who instead prefer to cook with local species. As biodiversity impacts are difficult to represent within an LCA framework, they are not assessed in this study. This omission reflects the methodological complexity of quantifying biodiversity within an LCA framework and the scope constraints of this thesis. It remains an important avenue for future research

Appendix F. Supporting Information on Functional Unit, Reference Flow and Sensitivity Analysis

In typical rice monocropping systems, a maximum of three harvests can be completed within one agricultural year. However, RP can only produce around two harvests annually, as the grow-out period of the prawn lasts longer than that of rice, meaning that the prawns must be harvested before the next cycle of rice can begin. Thus, to avoid scaling inconsistencies between the two systems, a temporal scale of one agricultural cycle will be considered. One agricultural cycle roughly covers between a four to six month period. This allows for a consistent functional unit and comparison not only between farms but between seasons and fields. The secondary data, collected where primary was not available, covers the 21st century (and preferably post-2020).

Three reference units were defined to show the contrasting benefits of these systems. The primary functional unit is mass-based, defined as providing 100 kg of prawn, and its monoculture rice equivalent of 282.34 kg, to consumers in Cambodia over one agricultural cycle from one field. The rice equivalent was derived by calculating the average prawn-to-rice output ratio across all RP farms, scaling prawn output to 100 kg, and determining the proportional rice quantity (which averaged 282.34 kg). This mass-based unit serves as the reference for the co-product allocation scenario, in which environmental burdens are divided between rice and prawn.

As OpenLCA does not permit two simultaneous functional flows as a reference unit, the MV and NDU functional units were assessed differently, with total farm-level emissions

allocated 100% to one product and subsequently rescaled by hand. These two functional units constitute the sensitivity analyses of this study. The MV functional unit is defined as providing USD 100 of combined prawn and rice, reflecting a proportional revenue split between the two products over one cycle in comparison to USD 100 of monoculture rice. Together, these three functional units allow the robustness of the primary results to be tested across economic and nutritional dimensions, capturing a broader range of the value that these farming systems deliver.

Figure 22
Detailed Flow Chart of 01.A.01



Appendix H. Allocation Explanation

The ISO 14044 establishes a clear methodological hierarchy when it comes to multi-functional processes. The first order of preference is to avoid allocation by subdividing processes or expanding system boundaries. The next order of preference follows the use of physical allocation, and then finally economic allocation when the other relationships do not apply. As system expansion was not feasible within the scope of my research, mass allocation was chosen. The table below shows an example of how this was conducted.

Table 19

Unit Processes 01.A.01 Rice Prawn Production Allocation

Flow	Direction	Amount	Unit	Machrobachium Rosenbergii	Rice Prawn Paddy Rice	Σ
[G0253] petrol, unleaded, burned in machinery	Input	684.0	MJ	0.11	0.89	1
[G0358] rice seed, for sowing	Input	10.0	kg	0.00	1.00	1
[G0519] dolomite	Input	25.0	kg	0.11	0.89	1
[G1712] quicklime, in pieces, loose	Input	125.0	kg	0.85	0.85	1
[G2527] electricity, low voltage	Input	491.4	kWh	0.11	0.89	1
[G3028] transport, passenger, motor scooter, fleet average	Input	30.0	p·km	0.11	0.89	1
[G3073] transport, freight, lorry, 16–32 metric ton, diesel, EURO 4	Input	24.5	t·km	0.85	0.15	1
Chicken Manure Organic Fertiliser	Input	329.6	kg	0.11	0.89	1
Cow Manure Liquid Compost	Input	200.0	l	0.11	0.89	1
Machrobachium Rosenbergii from Nursery	Input	6728.0	Item(s)	0.00	1.00	1
NPK (20-20-15)	Input	10.0	kg	0.15	0.85	1
Pelleted Prawn Feed	Input	40.0	kg	0.85	0.15	1
Pelleted Prawn Feed	Input	60.0	kg	0.85	0.15	1
Prawn Feed: Crushed Snails	Input	20,000	kg	0.85	0.15	1
Rice Seed	Input	10.0	kg	0.00	1.00	1
[W0360] municipal solid waste	Output	0.8	kg	0.11	0.89	1

Note. Causal mass allocation with manually adjusted flows highlighted in bold font.

Appendix I.

Supporting Information on the Cut-Off of Animal Manure

Upstream emissions from animal manure (specifically cows, buffalo, and chickens) are flows not considered, as including the full livestock production processes would significantly skew the results due to the high environmental impacts associated with cattle rearing. Instead, only environmental emissions related to manure application and storage are considered. This approach is justified because livestock production processes in Ecoinvent may overestimate emissions compared to actual cattle-raising practices in Cambodia, where animals are often raised in low-input systems. Furthermore, most farmers obtain manure from neighboring farms, where it is treated as a by-product rather than a primary product. Including the full livestock production chain would also require allocation of environmental burdens, which could disproportionately shift impacts and reduce the representativeness of the results. Instead, only emissions related to the application and handling of manure were modelled.

Appendix J. Normalisation Results and Discussion

Figure 23

Normalization results for EF v3.0, excluding outlier values 01.A.02 and 03.A.01.

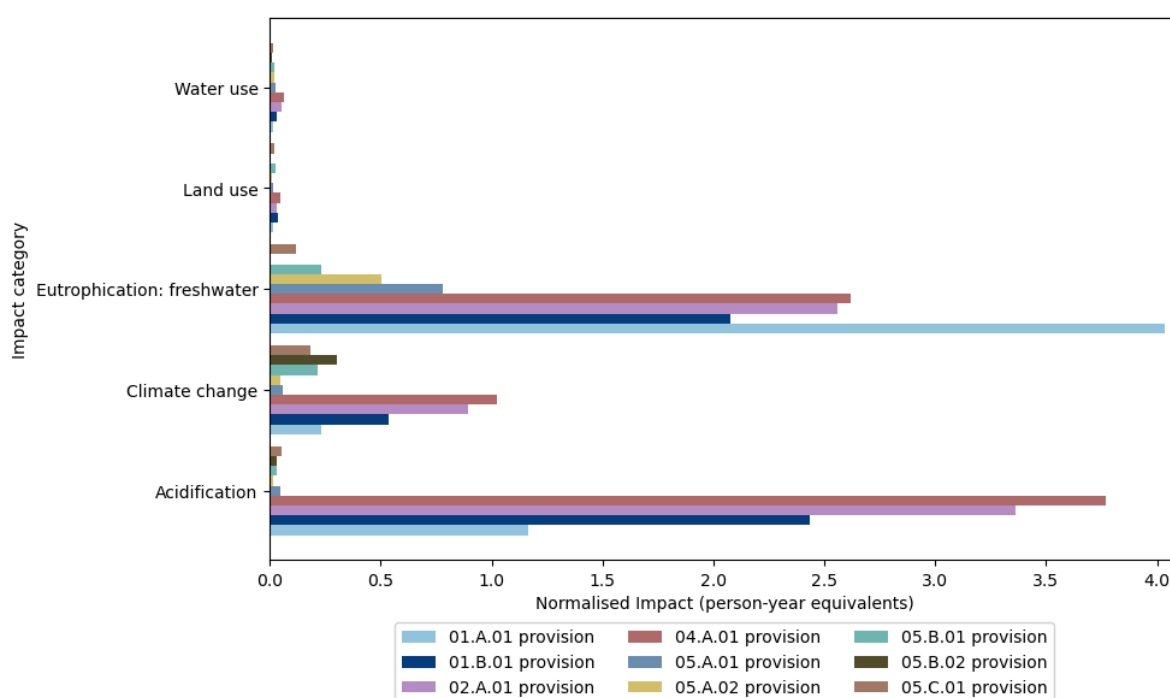


Figure 24

Averaged normalization results for EF v3.0, excluding outlier values 03.A.01

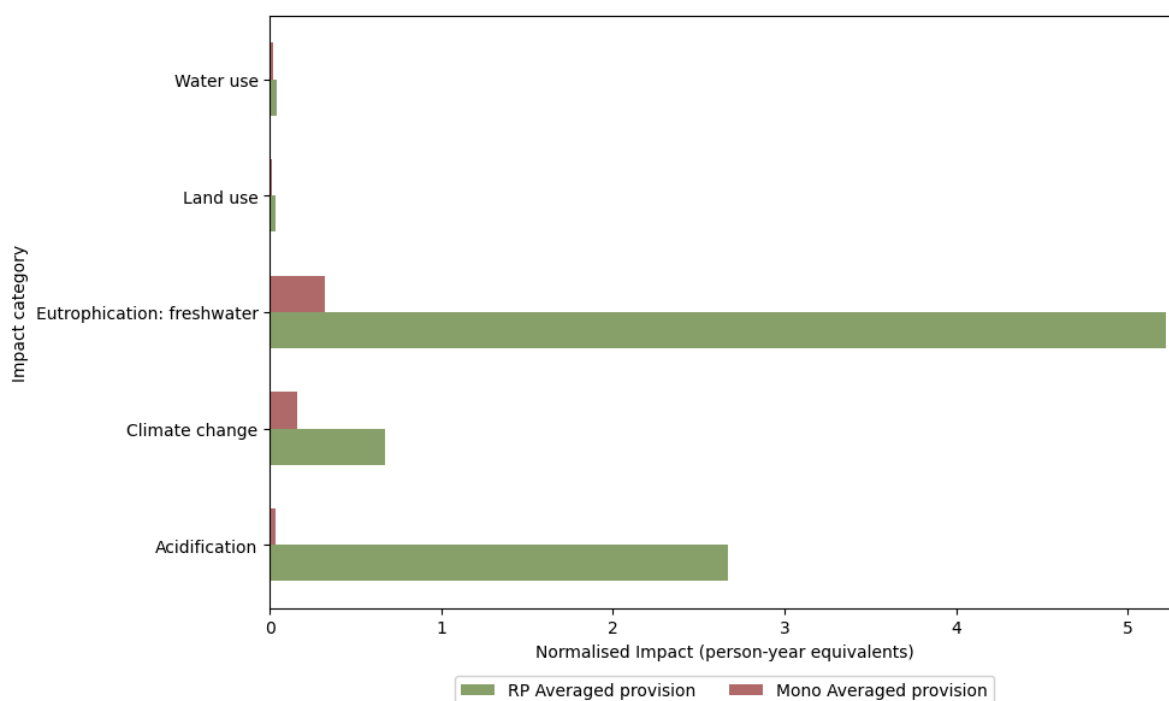


Figure 24 displays the overall normalisation results per IC excluding certain outliers, while figure 23 shows a more detailed breakdown per product system. There are clear peaks within the acidification and freshwater ecotoxicity categories, however, across the board it appears that RP farms have a higher impact. Upon closer inspection most of the Acidification impacts in the RP systems come from the storage and handling of cow manure in the liquid compost production.

Important here is that normalisation comes with limitations. The normalisation reference for certain ICs such as the toxicity categories are largely aggregated, not always well reported, and subject to data gaps. A full list of interventions for which characterisation factors are lacking and their corresponding results can be found in SM F. Other categories, including those represented in the graphs above, experience similar drawbacks, and may be incompletely represented. However, it can be seen that the general trends are maintained between characterisation and normalisation. Normalization does not constitute weighting, meaning results cannot be aggregated across ICs without additional steps.

Appendix K. LCA Biodiversity Limitations

Finally, an important limitation within the LCA methodology lies in the difficulty of representing biodiversity-related impacts. RP systems in Cambodia frequently utilise Golden Apple Snails (*Pomacea canaliculata*) as a feed source for prawn production. Golden Apple Snails are an invasive species first recorded in Cambodia in 1995 following intentional introduction for human consumption, but they subsequently became a widespread rice pest across several provinces, including Kampong Thom. As Golden Apple Snails are generally unpopular as a human food source in Cambodia compared with native snail species, their utilisation as aquaculture feed represents a potential opportunity for invasive species management while simultaneously reducing reliance on external feed inputs.

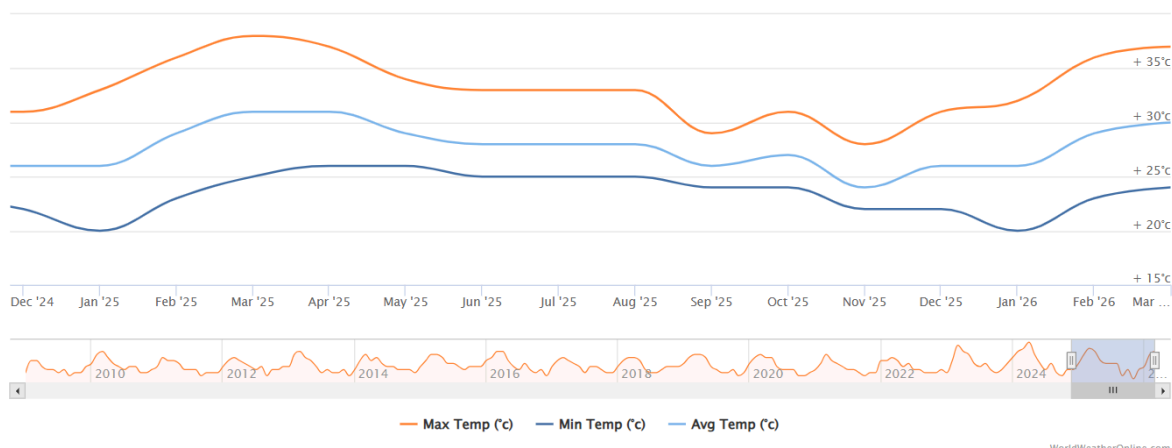
However, the ecological implications of this practice are complex and difficult to quantify within LCA. While harvesting Golden Apple Snails for prawn consumption may provide a biodiversity benefit by reducing populations of an invasive species, it may also reinforce their presence by converting an agricultural pest into a productive input. If demand for Golden Apple Snails as feed were to increase, there is a possibility that collection practices could unintentionally encourage their continued presence or redistribution. Moreover, the removal of invasive species does not automatically translate into measurable biodiversity improvements: ecosystem responses depend on a multitude of factors such as population dynamics, predation pressures, and interactions with native species. These trade-offs are difficult to capture using conventional LCA approaches, which are generally better suited to quantifying industrial systems than complex ecological relationships.

Appendix L. Kampong Thom Climate Data

Climate data from the Kampong Thom Area from 2024 onwards

Figure 25

Average Temperature For Kampong Thom From December 2024 To March 2026

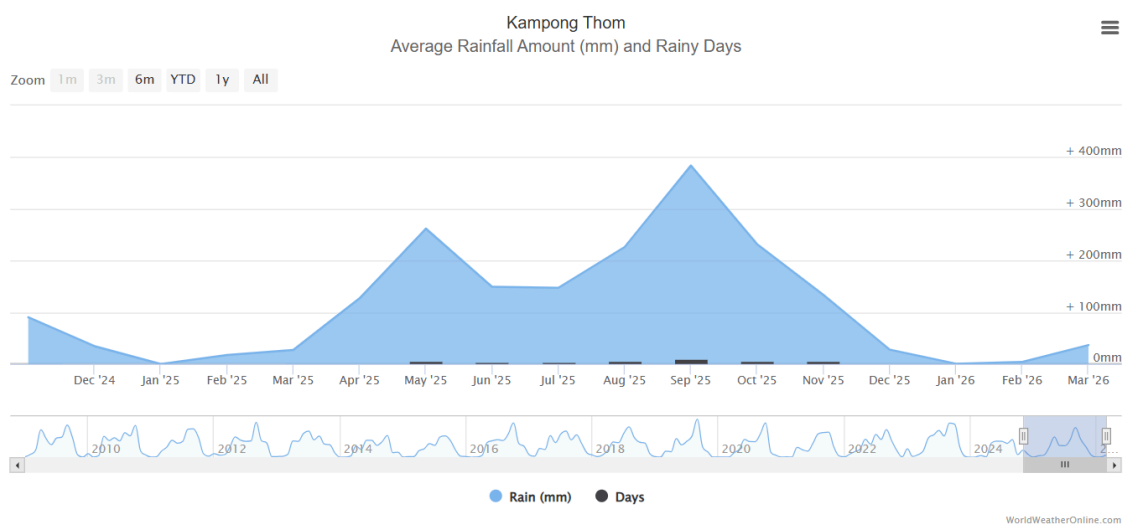


Note. From “Kampong Thom Annual Weather Averages,” by World Weather Online, n.d., World Weather Online.

<https://www.worldweatheronline.com/kampong-thom-weather-averages/kampong-thum/kh.aspx>

Figure 26

Average Rainfall For Kampong Thom From December 2024 To March 2026



Note. Adapted from “Kampong Thom Annual Weather Averages” by World Weather Online, n.d., World Weather Online.

<https://www.worldweatheronline.com/kampong-thom-weather-averages/kampong-thum/kh.aspx>