

Achieving the Three Pillars of Sustainability in Aquaculture

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This paper provides a large sample assessment of aquaculture governance using the Aquaculture Performance Indicators. More specifically, the paper draws our relationships between the of governance (also termed regulation, policy and management - see below) in enabling or undermining the social, environmental and economic 'pillars sustainability'. The scope of the paper is in line with the ambitions of the API framework and the large n sample (69 industries) supports the generalizations made. Nevertheless, the paper is broad and the inferences made on how governance affects these three pillars (and the various dimensions of the APIs) would benefit from more precise reasoning. The following points may help the readers achieve this.

1. Governance, management and regulation are used interchangeably at various points of the manuscript. For instance, line 103 brings the objective back to 'management' being the main focus of the paper, but the preceding paragraphs do not define the scope of such management (other than indicating 'sector management' is related to policy and regulation. In addition, 'Governance', 'National governance' and 'broader governance institutions' are referred to in the abstract and later in the paper (e.g para starting line 136) and are clearly differentiated in the API framework (Table S2), but are also not clearly explained. Greater precision is needed on the use of these terms, also explaining the contribution of the API framework to these related but still clearly different terms and steering processes.

2. Furthermore, it is unclear whether the public or private governance and regulation are being spoken about at some points. The assumption is that the paper focuses only on public governance, policy and regulation – although wider governance institutions remain very ambiguous - but this is often not made explicit. A clear set of definitions, with further embedding the literature beyond the Naylor et al. 2023 paper, would better position the paper. See recent papers by key scholars dealing with aquaculture governance such as Partelow, Vince, Bush, Froehlich, Lebel and Jolly.

3. As outlined in the opening paragraph the general claims made about the relationship between API dimensions are in line with the type of analysis the API framework offers (as seen in other papers – and also the Fisheries Performance Indicators). It is in fact a strength of the approach. Nevertheless, some of these broad statements could benefit from some further reflection, especially when qualifying claims are made about why certain relationships between variable are identified.

For example, line 132: "The importance of aquaculture regulation in social outcomes is unexpected given that the social dimension has remained at the periphery of aquaculture policy (Brugere et al., 2023; Ceballos-Concha et al., 2025), although the strong association of aquaculture regulation and wealth may contribute to this finding". This is a broad and rather selective interpretation. There is a literature on (write large) the social sustainability of aquaculture. Also what constitutes regulation in social outcomes is also not explained. On what basis can the link to social outcomes be then reduced to wealth?

Similarly, the claims starting on line 144 that "the quality of governance and the general economy are the least important to the economic dimension" needs some explanation beyond linking it 'immanent development'. For instance, Belton and Little's claim around immanent development is less about regulation and more about national and international 'intervention'. Their point is (1) interventionist approaches are less likely to have an impact on households in which aquaculture is but one livelihood activity and (2) that changes in the wider macro economy enable conditions for aquaculture expansion far beyond sector specific policy or regulation. That does not dismiss regulation, but puts regulation into a wider

governance context. While this level of detail is too much for the current paper, some further nuance would enable a more precise interpretation.

Note that the conclusion - "Collaborations with non-state 235 entities such as international development and philanthropic organizations may be the most viable option for sustainable development in countries with poor governance" – also risks contradicting the notion of immanent development.

Another example is the reference to Ostrom in line 192. While a general link is being made on the link between regulation in promoting collective action over aquaculture commons. Some nuance on what exactly is being collectively governed and what kinds of regulation at what level and by which actors would help here see Partelow, S., Schlüter, A., O Manlosa, A., Nagel, B., & Octa Paramita, A. (2022). Governing aquaculture commons. *Reviews in Aquaculture*, 14(2), 729-750. Some reflection on what is being regulated – as opposed to governed through what is now captured as 'informal' would help given some clearer explanation.

4. Finally, the last paragraph of the conclusion is also imprecise: Exogenous factors are important for aquaculture development, so policy makers must expand the focus beyond aquaculture regulation to impact social, economic and environmental outcomes. While I don't disagree – it would be difficult to do so after all - I also lack a more specific guidance on what might be done with such a statement. Earlier the authors also point out that wider regulation creates inefficiencies for instance. While links are made through the paper the relative impact of 'aquaculture regulation' relative to wider regulation is left hanging here. Said differently, is there any guidance on what can be attributed to the aquaculture sector and what should be left for regulation beyond the sector?

Reviewer #2

(Remarks to the Author)

This manuscript, "Achieving the Three Pillars of Sustainability in Aquaculture," analyzes a global dataset of 69 aquaculture systems using regression tree and random forest approaches to examine how governance, regulation, and enabling conditions relate to environmental, economic, and social sustainability outcomes.

The paper addresses an important and timely question: how different institutional and management factors relate to sustainability performance across aquaculture systems globally. The dataset underlying the Aquaculture Performance Indicators (APIs) is ambitious and potentially valuable for comparative analysis. The manuscript is clearly written and policy-relevant.

However, in its current form, the manuscript overinterprets correlational results as explanatory or causal insights, does not sufficiently address conceptual overlap between predictors and outcomes, and does not fully confront limitations inherent in expert-scored composite indices and non-random sampling. These issues weaken the strength of the policy conclusions.

I believe the study has merit, but substantial revision is required before publication in a high-impact journal.

Reviewer #3

(Remarks to the Author)

The objective of this paper titled "Achieving Three Pillars of Sustainability in Aquaculture" is to use a representative global dataset and analysis of 69 'aquaculture systems' (defined in paper) to understand the links between governance factors and other factors relating to sustainability pillars, identified as environmental, economic and social. I believe this manuscript needs a lot more work in order to increase text clarity, draw direct results-conclusion- suggested action courses, and thus be relevant to support policy makers' actions towards catalyzing sustainability in the aquaculture industry.

For example, it is confusing why the conclusion of the paper is that 'aquaculture policy alone' does not support a wholesome sustainability in the industry, despite the fact that this was confirmed to be the main major factor supporting the 3 pillars. The authors then suggest that "policy makers should extend their focus beyond aquaculture regulation" or towards the other factors studied, however the paper does not give one example of how exactly it is expected that policy development would target other areas to specifically (and indirectly) help aquaculture sustainability. How would policy makers focus on infrastructure or quality of management, for example? The citation of simple examples worldwide could help clarify the suggestion.

Throughout the manuscript, the authors repeatedly claim that little efforts were done to understand the importance of multiple pillars, or the sustainable economic and social pillars in aquaculture, which is not true. Social aspects of aquaculture has been one of FAO's long-standing focus and just based on the readily available published works, using different research approaches, some examples are:

Pratiwy et al. (2024) Exploring the depths: social-economic mapping for sustainable aquaculture communities and resilience, 183-195. In : Fauzi et al. *Essentials of Aquaculture Practices*. Springer.

Xu et al. (2024) Social benefits and environmental performance of aquaculture need to improve worldwide. *Commun Earth Environ* 5, 698.

Valenti et al. (2018) Indicator of sustainability to assess aquaculture systems. *Ecological Indicators* 88; 402-413.

Bunting, S.W. (2024) Principles of Sustainable Aquaculture: Promoting social, economic and environmental resilience.

Routledge. 376p.

Finally, some of the “discussions/conclusions” are not clearly supported by the results and the interaction between infrastructure and the strength of aquaculture regulation seems to be the only clear real novelty in the manuscript as it stands.

Specific suggestions:

Line 41; 79. Some references about environmental and social benefits of aquaculture being challenged dates more than 10, 15 years, and worldwide a lot has changed in knowledge, public view, and scientific advances. Better to use references that challenge the aquaculture benefits nowadays.

Line 67. Please give examples and reference of where/how ‘terrestrial aquaculture regulation is being applied to emerging aquaculture sectors’.

Line 87-89. ‘Lack of empirical evidence on relative importance... of economic and social benefits’. This statement is not true.

Line 129-130. Here it could also be relevant to add the certification labels that support sustainability and that, at least in some cases, can result in premium prices, as shown a paper from some of the authors of this very paper (Hammarlund et al., 2024. Eco-certification in aquaculture – economics incentives and effects.)

Line 151. “In the environmental dimension, research and development is and important contributor”. I cannot see that in Figure 2, as the mentioned circle looks like the same size as ‘management’ and ‘infrastructure’ factors and also ‘research’ circle is the same size for the economic pillar.

Line 164. “Infrastructure is an important contributor to social outcomes as it is necessary to provide healthcare...” This comment seems like a long jump to make between topics. Please clarify in details in text.

Line 196. What is meant by “collective approaches”? Naming it or referring it would help clarifying for the reader.

Line 207-208. “...there have been few studies that have assessed the multiple dimensions of sustainability at a global scale...” It would be good to give references of previous works to situate reader in the topic state-of-art. See previous general comment and examples of references.

Line 241. It is important to note that R&D spillovers are not unidirectional ‘from high-income countries’. Not only, but specially in the USA, there has been a lot of R&D being used brought from other countries where aquaculture is more developed such as France, Norway, Japan, and etc.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed my comments.

Reviewer #4

(Remarks to the Author)

The research is very relevant, and research and manuscript are mostly well-developed.

In my view, there are however two main concerns that should be improved.

Firstly, it is not clear, whether the research puts aquaculture management in the centre, or whether aquaculture management is one of many factors assessed (along data, collective action, markets, leadership, property rights...) and came out as the most contributing enabling factor as a result of your research. This should be better clarified and will likely facilitate to have a clearer line of argument to the Results and Discussion section.

Secondly, under Results and Discussions it is not always clear what part is results and what observations are simply discussion/hypothesis. Often, the two are mixed within the same sentence, resulting in claims that are either hypothetical or adopted from elsewhere. You should differentiate more strictly between your findings, comparison with other research findings, and what you take from both.

What follows, are some observations in more detail.

Lines 110 to 112. You write: “Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different management measures and other

enabling factors, such as national governance, impact environmental, economic and social outcomes” to then define aquaculture management as (Lines 112 to 116) “We define aquaculture management as the internal systems and processes responsible for implementing plans and policies to achieve aquaculture performance goals. Our measure of aquaculture management reflects performance in eight dimensions: disease control, genetic management, effluent control, antibiotic use, food safety, animal welfare, water access, and zoning management. “

It would be easier to understand, if you applied consistent language in both sentences and list all or none of the enabling factors considered, not just one: “Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different aquaculture management along other enabling factors (data, collective action, markets, leadership, property rights,) impact environmental, economic and social outcomes. We define aquaculture management as the internal systems and processes responsible for implementing plans and policies to achieve aquaculture performance goals. Our measure of aquaculture management reflects performance in eight dimensions: disease control, genetic management, effluent control, antibiotic use, food safety, animal welfare, water access, and zoning management.”?

Please also refer to my comment above. Maybe the goal was to assess all enabling factors equally, then the text should reflect this (“Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different enabling factors such as aquaculture management, data, collective action, markets, leadership, property rights, and others impact environmental, economic and social outcomes.”).

In my view, the incorporation of community-based management and its definition in the introduction (lines 116 to 124) is not necessary as it is rather confusing than contributing an addition to the outline. Better leave it out altogether. It makes more sense and is enough how you describe it in later sections.

Line 148/149. You write “It [your results] also shows that aquaculture sectors that can develop under strict regulations may be highly profitable (Misund et al., 2025).” I believe that this observation is not sustained by your results. The results show that there is a strong correlation between aquaculture management and economic outcomes, yes. However, the ‘high profitability’ is nowhere evident from your data.

Consequently, Lines 150 to 152 do not make sense to me as they are highly speculative.

Lines 164 to 166. This sentence/observation does not really make sense as better health and education systems in economic developed countries are most likely not (or only very limited) a consequence of aquaculture development benefits.

Lines 182 to 185: “Of the three pillars, national governance and economic conditions had the lowest predictive power in the economic dimension. This is broadly consistent with the rapid expansion of aquaculture in middle-income countries – an indication that, at least in aggregate, aquaculture in these countries is profitable.” Again, the conclusion is not fully accurate. The lowest predictive power is rather a contradiction to ‘high economic impact’, isn’t it? By no means is it an indication that aquaculture is profitable.

Line 303 to 305. “Collaborations with non-state entities such as international development and philanthropic organizations may be the most viable option for environmentally sustainable development in countries with poor governance.” This conclusion cannot really be drawn from your results. I believe it should be left out or be referenced if you draw from another research for comparison and/or developing your argument.

In addition, there are some minor details of technical nature or related to clarity as follows.

Line 143. You write “sustainable production”. I believe simply ‘production’ would be correct, as there is no guarantee that the production is sustainable. Otherwise, you need to be more specific about what production has achieved there (e.g. ‘economic gains’, ‘social benefits’, etc.).

Line 153: “Interestingly, aquaculture management, an element specific to aquaculture, predicts the most variation in social outcomes.” Delete ‘an element specific to aquaculture’ as this is self-explaining and the added relative sentence rather confusing. Better write: “Interestingly, aquaculture management predicts the most variation in social outcomes.”

Line 374/375. “Apart from 374 seaweed, which is primarily for non-consumptive uses...” Do you really mean non-consumptive, or rather ‘not for direct human food consumption’. As far as I know, seaweed is mostly farmed for consumption purposes, but not for human food production.

Line 397: should it be “identified at each node” rather than “identified at each noted”?

Figure 1: “Aquaculture systems assessed with the Aquaculture Performance Indicators (n=69).” Rather than the ‘aquaculture systems’, the figure is a map showing the geographic distribution of the aquaculture systems assessed. Hence, a title along the line ‘Figure 1: Map showing geographic distribution of assessed aquaculture systems’ would better describe the figure.

Text in Figure 5: In the graphic, you use ‘Community’ as one pillar of sustainability, a pillar elsewhere (including in the figure description) referred to as ‘social’. Changing it to ‘social’ would be consistent and make the graphic easier to understand.

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Response to Reviewer 1 for COMMSENV-26-0162-T

“Achieving the Three Pillars of Sustainability in Aquaculture”

This paper provides a large sample assessment of aquaculture governance using the Aquaculture Performance Indicators. More specifically, the paper draws our relationships between the of governance (also termed regulation, policy and management - see below) in enabling or undermining the social, environmental and economic ‘pillars sustainability’. The scope of the paper is in line with the ambitions of the API framework and the large n sample (69 industries) supports the generalizations made. Nevertheless, the paper is broad and the inferences made on how governance affects these three pillars (and the various dimensions of the APIs) would benefit from more precise reasoning. The following points may help the readers achieve this.

1. Governance, management and regulation are used interchangeably at various points of the manuscript. For instance, line 103 brings the objective back to ‘management’ being the main focus of the paper, but the preceding paragraphs do not define the scope of such management (other than indicating ‘sector management’ is related to policy and regulation. In addition, ‘Governance’, ‘National governance’ and ‘broader governance institutions’ are referred to in the abstract and later in the paper (e.g para starting line 136) and are clearly differentiated in the API framework (Table S2), but are also not clearly explained. Greater precision is needed on the use of these terms, also explaining the contribution of the API framework to these related but still clearly different terms and steering processes.

Thank you for your comment. We have revised the language to be consistent throughout, and we have added definitions for ‘management’ and ‘national governance’. We add the following text “Here, we define aquaculture management as the internal systems and processes responsible for implementing plans and policies to achieve aquaculture performance goals. Our measure of aquaculture management reflects performance in eight dimensions: disease control, genetic management, effluent control, antibiotic use, food safety, animal welfare, water access, and zoning management. Similar to fisheries, management can be operationalized at local, provincial, and national levels and led by public or private actors (Bush, 2024). It is increasingly recognized that de-centralized approaches, such as community-based management, where non-state actors play a more prominent role in management and decision-making, are important to achieving sustainability objectives in aquaculture as it relies on shared resources (Vince and Haward, 2017; Partelow et al., 2022; Jolly et al., 2023). According to

this definition, management is a distinct concept from the quality of state, termed ‘National governance and economy’. This measure reflects regulatory quality, rule of law, control of corruption, political stability, accountability, and macroeconomics of the government.”

2. Furthermore, it is unclear whether the public or private governance and regulation are being spoken about at some points. The assumption is that the paper focuses only on public governance, policy and regulation – although wider governance institutions remain very ambiguous - but this is often not made explicit. A clear set of definitions, with further embedding the literature beyond the Naylor et al. 2023 paper, would better position the paper. See recent papers by key scholars dealing with aquaculture governance such as Partelow, Vince, Bush, Froehlich, Lebel and Jolly.

This is a great point, and we apologize for overlooking this in our original submission. We have revised the last paragraph of the introduction to clarify that our definition of management includes public and private approaches. We also appreciate the paper suggestions and we have included many of the papers in the revised text.

3. As outlined in the opening paragraph the general claims made about the relationship between API dimensions are in line with the type of analysis the API framework offers (as seen in other papers – and also the Fisheries Performance Indicators). It is in fact a strength of the approach. Nevertheless, some of these broad statements could benefit from some further reflection, especially when qualifying claims are made about why certain relationships between variable are identified.

Thank you for the comment. We can see now that our discussion of the results requires deeper reflection. We have rewritten much of the text in the results section to discuss our findings and the literature in greater detail.

For example, line 132: “The importance of aquaculture regulation in social outcomes is unexpected given that the social dimension has remained at the periphery of aquaculture policy (Brugere et al., 2023; Ceballos-Concha et al., 2025), although the strong association of aquaculture regulation and wealth may contribute to this finding”. This is a broad and rather selective interpretation. There is a literature on (write large) the social sustainability of aquaculture. Also what constitutes regulation in social outcomes is also not explained. On what basis can the link to social outcomes be then reduced to wealth?

We provide further reflection here by providing examples of how self-managing arrangements have been successful in achieving environmental and social objectives, referencing Jolly et al. (2023) and Osmundsen et al. (2021). We further elaborate on the correlation of aquaculture management and economic

development status, and how this may contribute to a positive association between aquaculture management and social outcomes, such as access to education and healthcare.

Similarly, the claims starting on line 144 that “the quality of governance and the general economy are the least important to the economic dimension” needs some explanation beyond linking it ‘immanent development’. For instance, Belton and Little’s claim around immanent development is less about regulation and more about national and international ‘intervention’. Their point is (1) interventionist approaches are less likely to have an impact on households in which aquaculture is but one livelihood activity and (2) that changes in the wider macro economy enable conditions for aquaculture expansion far beyond sector specific policy or regulation. That does not dismiss regulation, but puts regulation into a wider governance context. While this level of detail is too much for the current paper, some further nuance would enable a more precise interpretation.

We add text to build a stronger case that the rapid expansion of aquaculture is in itself a sign of profitability. We also provide a more nuanced discussion of capitalist development of aquaculture in Southeast Asia and how it is more driven by private sector investment rather than state-government and how this has yielded greater development impacts from both economic and social standpoints.

Note that the conclusion - “Collaborations with non-state 235 entities such as international development and philanthropic organizations may be the most 236 viable option for sustainable development in countries with poor governance” – also risks contradicting the notion of immanent development.

We clarify the statement in the conclusion that collaboration may be necessary for environmentally sustainable development. Our results are consistent with the notion that immanent development can result in more economically and socially sustainable aquaculture; however, we find a stronger association between “national governance and economics” and “environmental sustainability”, and such non-state entities may provide a pathway to minimize environmental effects.

Another example is the reference to Ostrom in line 192. While a general link is being made on the link between regulation in promoting collective action over aquaculture commons. Some nuance on what exactly is being collectively governed and what kinds of regulation at what level and by which actors would help here see Partelow, S., Schlüter, A., O Manlosa, A., Nagel, B., & Octa Paramita, A. (2022). Governing

aquaculture commons. Reviews in Aquaculture, 14(2), 729-750. Some reflection on what is being regulated – as opposed to governed through what is now captured as ‘informal’ would help given some clearer explanation.

Thank you for the comment. We provide more nuance to the text in the last paragraph to reflect insights from Partelow et al. 2022. We discuss how, under strong management, collective approaches are more likely to address the social commons, such as sharing of knowledge and infrastructure, as the institutions to govern shared environmental resources are already in place. On the other hand, under weaker management, greater effort is required to develop the second-order institutions to govern shared environmental resources, as the institutions are often less-developed under these circumstances.

4. Finally, the last paragraph of the conclusion is also imprecise: Exogenous factors are important for aquaculture development, so policy makers must expand the focus beyond aquaculture regulation to impact social, economic and environmental outcomes. While I don't disagree – it would difficult to do so after all - I also lack a more specific guidance on what might be done with such a statement. Earlier the authors also point out that wider regulation creates inefficiencies for instance. While links are made through the paper the relative impact of ‘aquaculture regulation’ relative to wider regulation is left hanging here. Said differently, is there any guidance on what can be attributed to the aquaculture sector and what should be left for regulation beyond the sector?

We add the following text to the concluding paragraph “Collaborative approaches among state and non-state actors may facilitate its sustainable development. For instance, the use of public-private partnerships may strengthen investment in infrastructure (Partelow et al., 2022; Murekezi et al., 2024). However, coordinated efforts should concurrently strengthen management capacity as both were important for achieving the three pillars of sustainable aquaculture development.”

Response to Reviewer 2 for COMMSENV-26-0162-T

“Achieving the Three Pillars of Sustainability in Aquaculture”

This manuscript, “Achieving the Three Pillars of Sustainability in Aquaculture,” analyzes a global dataset of 69 aquaculture systems using regression tree and random forest approaches to examine how governance, regulation, and enabling conditions relate to environmental, economic, and social sustainability outcomes. The paper addresses an important and timely question: how different institutional and management factors relate to sustainability performance across aquaculture systems globally. The dataset underlying the Aquaculture Performance Indicators (APIs) is ambitious and potentially valuable for comparative analysis. The manuscript is clearly written and policy-relevant.

However, in its current form, the manuscript overinterprets correlational results as explanatory or causal insights, does not sufficiently address conceptual overlap between predictors and outcomes, and does not fully confront limitations inherent in expert-scored composite indices and non-random sampling. These issues weaken the strength of the policy conclusions.

I believe the study has merit, but substantial revision is required before publication in a high-impact journal.

Thank you for your comments. We regretfully see that we have implied causality in several cases, and despite our best efforts, we do not fully discuss the limitations of our methods. We elaborate further on our specific revisions below.

Major Comments

1. Conceptual overlap between predictors and outcomes (risk of circular inference)

A central conclusion of the paper is that aquaculture regulation is the most important cross-cutting factor explaining sustainability outcomes (e.g., Results section).

However, several environmental and social performance indicators appear conceptually linked to regulatory structures themselves (see Tables S1–S2). For example:

- environmental compliance,
- discharge control,
- antibiotic use,

- welfare practices,
- zoning and management,

are embedded in both performance outcomes and regulatory input metrics. This creates a risk that the analysis partially measures:

systems scoring highly on regulation also scoring highly on metrics partly defined by regulation.

The manuscript should explicitly address this potential circularity and clarify:

- how independence between predictors and outcomes is ensured,
- whether overlapping constructs were tested for robustness,
- whether results hold after excluding regulation-adjacent outcome metrics.

Without this clarification, the central conclusion risks being tautological rather than explanatory.

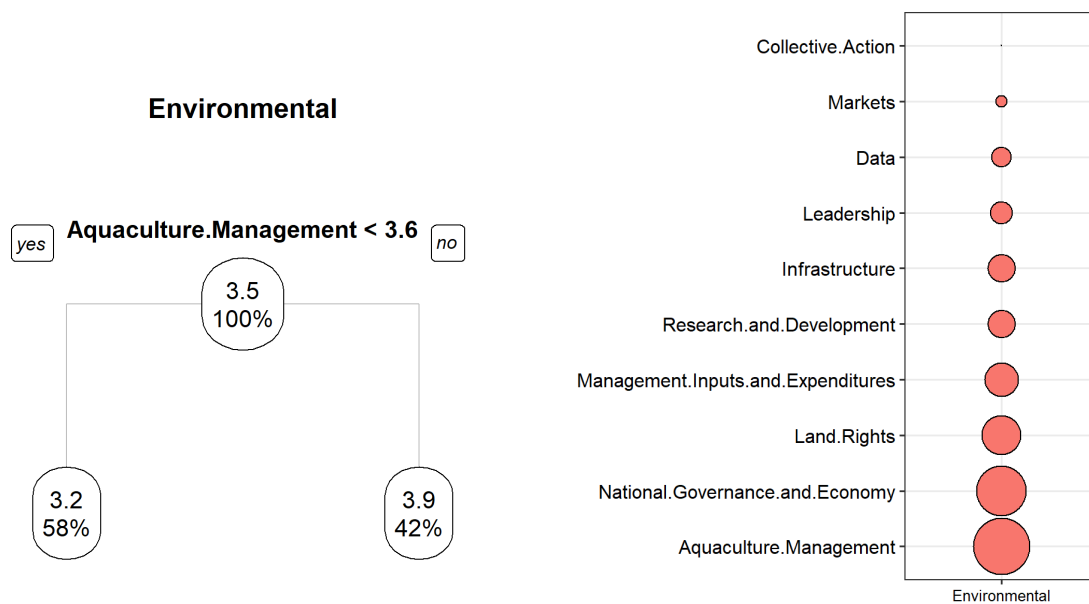
Thank you for your comment. We define inputs as the resources, actions, and efforts invested to reach an output. Outputs are the measurable outcomes relating to environmental, economic, and social performance. Outputs are hypothesized to be influenced by inputs, and thus are conceptually linked. The two types of indicators were designed to be able to test hypotheses on how inputs (e.g., management) affect outputs.

Compliance with environmental law is an output that measures the proportion of production that is compliant with environmental laws. It does not reflect the degree of regulation, rather compliance with regulation, which is used as a proxy for environment performance. It is an output because it is a direct quantifiable outcome of the sector and it is hypothesized to be influenced by inputs such as enforcement.

The other four indicators mentioned above are input indicators and are four of the eight indicators that make up aquaculture management. These inputs measure the extent to which various management approaches or mechanisms are used. For instance, the input “discharge control” reflects the degree to which different economic instruments are used in effluent management (e.g., market-based permits, pollution taxes, command and control approaches, etc.). The only output related to these inputs is “Impacts of discharge- nutrient emissions”. This measures the impact of discharge on the surrounding environment, and is measured on a scale of “positive impact”, “no impact”, “minor impact”,

“significant impact”, “severe impact”. The inputs and outputs were purposefully developed to examine the relationship between them and this is what we are interested in measuring.

We removed environmental compliance from our measure of environmental performance and re-run the models. The variance explained by the random forest model was similar 27% compared to 33% in the original model, and the predictive significance of aquaculture management remained the same. Thus, giving us confidence that the results are robust.



2. Causal interpretation exceeds what the methods support

The manuscript frequently interprets variable importance from random forest models as evidence that certain factors drive, contribute to, or are required for sustainability outcomes.

However, random forests identify predictive associations, not causal mechanisms. Several alternative explanations remain plausible, including:

- reverse causality (wealthier systems simultaneously achieve higher performance and stronger regulation),
- omitted institutional variables,
- shared underlying development gradients.

The authors should substantially moderate causal language and explicitly distinguish:

- predictive association,
- structural explanation,
- causal inference.

At minimum, discussion sections should acknowledge that results are consistent with institutional theory rather than definitive tests of it.

Thank you for your comment. We revise the language throughout the results and discussion to remove casual language and instead discuss the results in terms of their predictive association. We also rewrite the text to clarify and distinguish the predictive associations with the explanations provided by supporting literature.

3. Limited theoretical advancement

The manuscript confirms a broadly established expectation within institutional economics and sustainability governance: that governance quality and regulation correlate with improved outcomes.

While empirical confirmation is valuable, the manuscript currently does not articulate a clear theoretical advance beyond existing literature.

The authors could strengthen the contribution by:

- proposing a mechanism explaining why regulation simultaneously aligns environmental, economic, and social outcomes,
- situating findings within debates on institutional complementarities or development pathways,
- clarifying whether aquaculture differs from fisheries or agriculture in systematic ways.

At present, the theoretical contribution feels implicit rather than explicit.

We found this comment a bit surprising, as we did not envisage a theoretical contribution in this paper. The theory of the three pillars of sustainability is well established and predicts positive correlations between the three pillars when sufficient measures, which in most cases is regulation, are taken to promote sustainability. The Aquaculture Performance Indicators (and the Fisheries Performance Indicators) are set within this framework and the specific theory for the APIs can be found in Garlock et al. (2024). The contribution of this paper is applied in that it investigates the association empirically for the first time in the

case of aquaculture. As to our knowledge, the API data set is the first and so far only data set that allows such an analysis. We obviously did not do a good enough job at clarifying how the difference between fisheries and aquaculture is about the degree of control with the production process, although as argued by Anderson (2002), this can be thought of as a continuum where only fisheries are true open access and only aquaculture provides closed production systems, but where highly regulated fisheries may constitute a more controlled production process than extensive aquaculture operations.

4. Sampling strategy limits generalizability

The dataset represents an opportunistic, non-random sample of aquaculture systems (Methods section). This is understandable given data constraints but has important implications.

Systems included are likely those with:

- available collaborators,
- institutional organization,
- measurable governance structures.

This may bias results toward more formalized sectors. The manuscript should more clearly discuss:

- potential selection bias,
- limits to global inference,
- whether findings apply to informal or emerging aquaculture systems.

Currently, policy recommendations appear broader than the sampling design supports.

Yes, we indicate in the text that our sample is based on where we could find knowledgeable collaborators to assess aquaculture sectors. However, we did carefully consider global production patterns when we sought out collaborators to score certain sectors. Still, there is some selection bias present despite our best efforts. We revise the text in the methods section to elaborate on the limitations of our dataset including the addition of a statement that selection bias is present. We further clarify that our data represent 41% of global aquaculture production quantity and 37% of global production value, and that the species

composition of our dataset closely mirrors that of global production with the exception of seaweed. However, seaweed is often excluded from studies regarding aquaculture food production/aquaculture management as it is primarily for non-consumptive purposes. The species or species groups represented covers 58% of total aquaculture production quantity and 66% of the value, and the countries represented covers 89% of total aquaculture production quantity and 90% of the value. Thus, it is the most comprehensive dataset available with comparable data in the economic, environmental and social dimensions.

5. Measurement uncertainty is not addressed

API scores are derived partly from expert judgment, interviews, and proxy data. While vetting procedures are described, the manuscript does not quantify uncertainty arising from scoring decisions.

Possible improvements include:

- discussion of scorer variability,
- sensitivity tests,
- uncertainty ranges around aggregated scores.

Given that machine learning models are applied to constructed indices, uncertainty propagation becomes particularly important.

There is some degree of uncertainty in the scores, as with all data. An extensive manual was developed to provide justifications and examples of how to score each individual metric. The API approach uses multiple metrics that are aggregated and can triangulate more accurate values, rather than measuring few indicators with very high precision. There was also significant effort put into seeking out on-the-ground experts with a high level of knowledge regarding the specific system. Nonetheless, we add a statement in the methods section acknowledging there is some degree of uncertainty in the experts' scores and that this may vary between observations depending on how much data is available for a specific sector.

6. Interpretation of random forest importance metrics

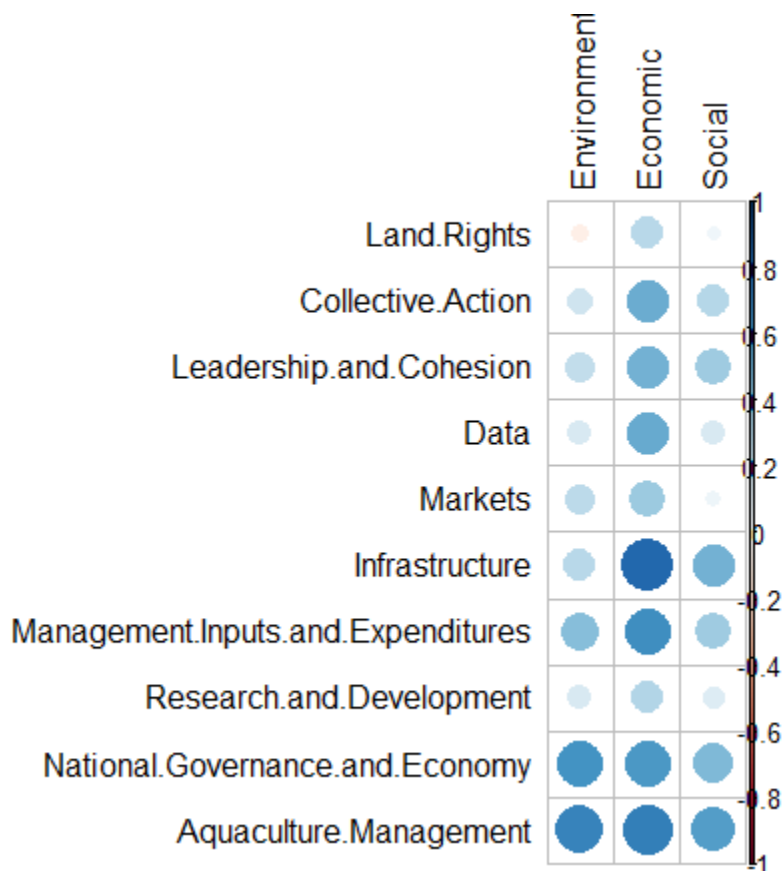
Figure 2 presents variable importance based on permutation error increases. These values indicate predictive relevance but do not reveal:

- direction of effects,

- marginal magnitudes,
- interaction structures beyond those explicitly visualized.

The manuscript sometimes treats importance rankings as structural dominance among factors. The authors should clarify interpretational limits and avoid implying quantitative policy prioritization based solely on importance scores.

In hindsight, we agree that we implied a ranking of importance in discussing our results. We revise the text to remove ranking statements and to discuss the variables in terms of predictive association. We also include the following figure in the supplementary text to support our discussion of the direction of the relationship.



7. Interaction between infrastructure and regulation is underdeveloped

The interaction analysis (Figure 5) is one of the most interesting findings:

- infrastructure improves outcomes under strong regulation,

- but may worsen environmental outcomes under weak regulation.

This result has clear theoretical and policy relevance but is comparatively underemphasized relative to regulation importance claims.

I encourage the authors to elevate this interaction as a central contribution and expand its conceptual interpretation.

Thank you for the comment. We also find this result particularly interesting. We elaborate on this finding in the results and discussion section and also bring out policy recommendations regarding this finding in the conclusions section.

Minor Comments

1. The Introduction would benefit from a clearer statement of the study's specific hypothesis rather than broad motivation.

We have rewritten the end of the introduction to provide a clearer vision for the study and to embedded the current study within the existing literature.

2. Results and Discussion sections occasionally blend interpretation and literature review; clearer separation would improve readability.

We have rewritten the results and discussion to clarify statements regarding our findings and support from the literature.

3. Some conclusions (e.g., "policy makers must expand the focus...") should be more carefully tied to empirical limits.

We have revised the conclusions linking them directly to the empirical findings.

4. Consider adding a conceptual framework figure linking inputs → governance mechanisms → sustainability outcomes.

While this is an interesting concept, we feel this out of the scope of this paper.

5. Clarify terminology consistency between "social," "community," and "societal" dimensions.

We made the terminology consistent throughout the manuscript using social.

Strengths

Despite the concerns above, the manuscript has several notable strengths:

- A rare and ambitious global comparative dataset.
- Integration across environmental, economic, and social pillars.
- Clear writing and strong policy relevance.

- An analytically interesting infrastructure–regulation interaction.

These elements provide a solid foundation for a strong contribution following revision.

Recommendation Major Revision

The manuscript addresses an important topic and uses a valuable dataset, but revisions are needed to:

- reduce causal overinterpretation,
- address conceptual overlap,
- clarify methodological limits,
- sharpen theoretical contribution.

With these improvements, the paper could make a meaningful contribution to sustainability and aquaculture governance literature.

Thank you for your helpful comments. We hope you find our responses satisfactory.

Response to Reviewer 3 for COMMSENV-26-0162-T

“Achieving the Three Pillars of Sustainability in Aquaculture”

The objective of this paper titled “Achieving Three Pillars of Sustainability in Aquaculture” is to use a representative global dataset and analysis of 69 ‘aquaculture systems’ (defined in paper) to understand the links between governance factors and other factors relating to sustainability pillars, identified as environmental, economic and social. I believe this manuscript needs a lot more work in order to increase text clarity, draw direct results-conclusion- suggested action courses, and thus be relevant to support policy makers’ actions towards catalyzing sustainability in the aquaculture industry.

Thank you for your helpful comments. We have made significant revisions to the results and concluding sections of the paper. Please see the individual responses below.

For example, it is confusing why the conclusion of the paper is that ‘aquaculture policy alone’ does not support a wholesome sustainability in the industry, despite the fact that this was confirmed to be the main major factor supporting the 3 pillars. The authors then suggest that “policy makers should extend their focus beyond aquaculture regulation” or towards the other factors studied, however the paper does not give one example of how exactly it is expected that policy development would target other areas to specifically (and indirectly) help aquaculture sustainability. How would policy makers focus on infrastructure or quality of management, for example? The citation of simple examples worldwide could help clarify the suggestion.

Thank you for pointing this out. Aquaculture management was a strong predictor of performance across all three dimensions; however, in the cases of economic and social performance, other important predictors were found such as infrastructure. We revise the concluding text to point out some approaches for policy development that could encompass these broader elements. We revise the concluding text to “Collaborative approaches among state and non-state actors may facilitate its sustainable development. For instance, the use of public-private partnerships may strengthen investment in infrastructure (Partelow et al., 2022; Murekezi et al., 2024). However, coordinated efforts should concurrently strengthen management capacity as both were important for achieving the three pillars of sustainable aquaculture development.”

Throughout the manuscript, the authors repeatedly claim that little efforts were done to understand the importance of multiple pillars, or the sustainable economic and social pillars in aquaculture, which is not true. Social aspects of aquaculture has been one of

FAO's long-standing focus and just based on the readily available published works, using different research approaches, some examples are:

Pratiwy et al. (2024) Exploring the depths: social-economic mapping for sustainable aquaculture communities and resilience, 183-195. In : Fauzi et al. Essentials of Aquaculture Practices. Springer.

Xu et al. (2024) Social benefits and environmental performance of aquaculture need to improve worldwide. Commun Earth Environ 5, 698.

Valenti et al. (2018) Indicator of sustainability to assess aquaculture systems. Ecological Indicators 88; 402-413.

Bunting, S.W. (2024) Principles of Sustainable Aquaculture: Promoting social, economic and environmental resilience. Routledge. 376p.

In hindsight, we realize that we poorly phrased this sentence. We revise it to “...developing tailored policies is challenged by a limited number of studies examining the economic and social benefits together and across the diverse contexts that aquaculture operates, as well as the diversity of methodological approaches, including inconsistencies in quantifying social benefits (Valenti et al., 2018; Belton et al., 2020; Krause et al., 2020; Xu et al., 2024; Castillo et al., 2026).”

Finally, some of the “discussions/conclusions” are not clearly supported by the results and the interaction between infrastructure and the strength of aquaculture regulation seems to be the only clear real novelty in the manuscript as it stands.

We have revised the conclusions linking them directly to the empirical findings, and we have elaborated on the interaction between infrastructure and aquaculture management.

Specific suggestions:

Line 41; 79. Some references about environmental and social benefits of aquaculture being challenged dates more than 10, 15 years, and worldwide a lot has changed in knowledge, public view, and scientific advances. Better to use references that challenge the aquaculture benefits nowadays.

We have removed the Naylor et al., 2009 and Zhang et al., 2025 and added Yuan et al., 2019, Belton et al., 2020a, Xu et al., 2024, and Castillo et al., 2025; 2026.

Line 67. Please give examples and reference of where/how 'terrestrial aquaculture regulation is being applied to emerging aquaculture sectors'.

We add an example: The regulation of nitrogen in the EU and reference Jacobsen et al. 2016.

Line 87-89. 'Lack of empirical evidence on relative importance... of economic and social benefits'. This statement is not true.

We can see now that this statement requires more nuance. We revise it to "limited number of comparative studies drawing insights across contexts such as technologies and species as well as methodological limitations, including inconsistencies in quantifying social benefits."

Line 129-130. Here it could also be relevant to add the certification labels that support sustainability and that, at least in some cases, can result in premium prices, as shown a paper from some of the authors of this very paper (Hammarlund et al., 2024. Eco-certification in aquaculture – economics incentives and effects.)

This is a relevant point. We have integrated it into the text.

Line 151. "In the environmental dimension, research and development is and important contributor". I cannot see that in Figure 2, as the mentioned circle looks like the same size as 'management' and 'infrastructure' factors and also 'research' circle is the same size for the economic pillar.

That is correct. Management, infrastructure and R&D are important predictors. We have rephrased the text accordingly.

Line 164. "Infrastructure is an important contributor to social outcomes as it is necessary to provide healthcare..." This comment seems like a long jump to make between topics. Please clarify in details in text.

Social performance is measured primarily through returns to labor, access to healthcare and other community services as well as the proportion of local labor. We have rewritten this text to provide deeper reflection on the importance of infrastructure to social outcomes.

Line 196. What is meant by "collective approaches"? Naming it or referring it would help clarifying for the reader.

Thank you for this comment, and sorry we did not clearly articulate the meaning behind this. We use collective approaches to encompass various forms of

collective action including cooperatives, associations, and clusters, which can be formal or informally organized. We revise the text to reflect this.

Line 207-208. "...there have been few studies that have assessed the multiple dimensions of sustainability at a global scale..." It would be good to give references of previous works to situate reader in the topic state-of-art. See previous general comment and examples of references.

We have elaborated on this discussion and incorporated the suggested references.

Line 241. It is important to note that R&D spillovers are not unidirectional 'from high-income countries'. Not only, but specially in the USA, there has been a lot of R&D being used brought from other countries where aquaculture is more developed such as France, Norway, Japan, and etc.

Good point. We add this nuance to the text and include adoption of RAS technology in the US using Ropicki et al. (2024) as a reference.

Response to Reviewer 4 for COMMSENV-26-0162-T

“Achieving the Three Pillars of Sustainability in Aquaculture”

The research is very relevant, and research and manuscript are mostly well-developed.

In my view, there are however two main concerns that should be improved.

Firstly, it is not clear, whether the research puts aquaculture management in the centre, or whether aquaculture management is one of many factors assessed (along data, collective action, markets, leadership, property rights...) and came out as the most contributing enabling factor as a result of your research. This should be better clarified and will likely facilitate to have a clearer line of argument to the Results and Discussion section.

Thank you for pointing this out. We agree that the text points to aquaculture management as the main focus, and this was not our intent. Our intent was to investigate the impact of the whole governance system with a particular focus on the relative importance of different parts of it. We have revised the text to equally acknowledge all enabling factors assessed.

Secondly, under Results and Discussions it is not always clear what part is results and what observations are simply discussion/hypothesis. Often, the two are mixed within the same sentence, resulting in claims that are either hypothetical or adopted from elsewhere. You should differentiate more strictly between your findings, comparison with other research findings, and what you take from both.

Thank you for the comment. We rewrote sentences in the results and discussion to improve the distinction between our results and the discussion of the existing literature. We modified the language and separated sentences presenting our findings with sentences discussing the literature.

What follows, are some observations in more detail.

Lines 110 to 112. You write: “Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different management measures and other enabling factors, such as national governance, impact environmental, economic and social outcomes” to then define aquaculture management as (Lines 112 to 116) “We define aquaculture management as the internal systems and processes responsible for implementing plans

and policies to achieve aquaculture performance goals. Our measure of aquaculture management reflects performance in eight dimensions: disease control, genetic management, effluent control, antibiotic use, food safety, animal welfare, water access, and zoning management. “

It would be easier to understand, if you applied consistent language in both sentences and list all or none of the enabling factors considered, not just one: “Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different aquaculture management along other enabling factors (data, collective action, markets, leadership, property rights,) impact environmental, economic and social outcomes. We define aquaculture management as the internal systems and processes responsible for implementing plans and policies to achieve aquaculture performance goals. Our measure of aquaculture management reflects performance in eight dimensions: disease control, genetic management, effluent control, antibiotic use, food safety, animal welfare, water access, and zoning management.”?

Please also refer to my comment above. Maybe the goal was to assess all enabling factors equally, then the text should reflect this (“Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how different enabling factors such as aquaculture management, data, collective action, markets, leadership, property rights, and others impact environmental, economic and social outcomes.”).

Thank you for the suggestions. We revise the sentence as follows: “Here, we utilize an expanded version of the unique global dataset collected by Garlock et al. (2024) using the Aquaculture Performance Indicators (Figure 1) to examine how aquaculture management and other enabling factors, such as national governance, R&D, management inputs and expenditures, infrastructure, markets, data, leadership and cohesion, collective action, and land rights, impact environmental, economic and social outcomes.” We also modified the text throughout the text to make it clear that our goal was to assess all enabling factors.

In my view, the incorporation of community-based management and its definition in the introduction (lines 116 to 124) is not necessary as it is rather confusing than contributing an addition to the outline. Better leave it out altogether. It makes more sense and is enough how you describe it in later sections.

Thank for the suggestion. We have removed the definition of community-based management from the introduction.

Line 148/149. You write “It [your results] also shows that aquaculture sectors that can develop under strict regulations may be highly profitable (Misund et al., 2025).” I believe that this observation is not sustained by your results. The results show that there is a strong correlation between aquaculture management and economic outcomes, yes. However, the ‘high profitability’ is nowhere evident from your data.

Yes, we agree that high profitability was too strong of phrasing. We revise the sentence to “It also shows that aquaculture sectors that can develop under strict regulations can be economically viable”

Consequently, Lines 150 to 152 do not make sense to me as they are highly speculative.

We rewrite the sentence and add examples from the literature showing that innovation and increases in scale are adaptations to strict environmental regulation. We write “Studies have shown that innovations (Osmundsen et al., 2022; Asche et al., 2022; Ropicki et al., 2024; Larsen et al., 2025) as well as economies of scale (Nielsen et al., 2016; Pandey et al., 2023; Engle et al., 2025) have been important responses for coping with strict environmental regulation.”

Lines 164 to 166. This sentence/observation does not really make sense as better health and education systems in economic developed countries are most likely not (or only very limited) a consequence of aquaculture development benefits.

Thank you for the comment. We see now that this idea was not well-articulated. We have rewritten the sentence for clarity as follows “There are also several studies highlighting the importance of aquaculture management and policy in the equitable and fair distribution of aquaculture benefits as well as improving the well-being of the broader community (e.g., Krause et al., 2015; Brugere et al., 2021).

Lines 182 to 185: “Of the three pillars, national governance and economic conditions had the lowest predictive power in the economic dimension. This is broadly consistent with the rapid expansion of aquaculture in middle-income countries – an indication that, at least in aggregate, aquaculture in these countries is profitable.” Again, the conclusion is not fully accurate. The lowest predictive power is rather a contradiction to ‘high economic impact’, isn’t it? By no means is it an indication that aquaculture is profitable.

Thank you for pointing this out. We revise these sentences to better articulate that aquaculture has expanded in countries with varying levels of state-government performance and thus it appears that state-level governance plays a weaker role in the economic success of aquaculture, where the rapid growth of aquaculture is a reflection of economic success. We further nuance this by pointing out that aquaculture development has been most successful in places where private sector development has fueled growth as opposed to development with heavy support and intervention from state-government as shown by Belton and Little (2011).

Line 303 to 305. "Collaborations with non-state entities such as international development and philanthropic organizations may be the most viable option for environmentally sustainable development in countries with poor governance." This conclusion cannot really be drawn from your results. I believe it should be left out or be referenced if you draw from another research for comparison and/or developing your argument.

We revise the sentence to: "In countries with poor governance, non-governmental, international development and philanthropic organizations can play an important role in environmentally sustainable development (Anh et al., 2011; Vince and Haward, 2017; Karim and Almira, 2023)."

In addition, there are some minor details of technical nature or related to clarity as follows.

Line 143. You write "sustainable production". I believe simply 'production' would be correct, as there is no guarantee that the production is sustainable. Otherwise, you need to be more specific about what production has achieved there (e.g. 'economic gains', 'social benefits', etc.).

We revise it to "environmentally sustainable production" as we are referring to the aquaculture production in the North America and Europe who received the highest environmental scores.

Line 153: "Interestingly, aquaculture management, an element specific to aquaculture, predicts the most variation in social outcomes." Delete 'an element specific to aquaculture' as this is self-explaining and the added relative sentence rather confusing. Better write: "Interestingly, aquaculture management predicts the most variation in social outcomes."

Thank you. Revised to "Interestingly, aquaculture management predicts the most variation in social outcomes."

Line 374/375. “Apart from 374 seaweed, which is primarily for non-consumptive uses...”
Do you really mean non-consumptive, or rather ‘not for direct human food consumption’.
As far as I know, seaweed is mostly farmed for consumption purposes, but not for human food production.

We revised this to “seaweed, which is not primarily for direct human consumption,”

Line 397: should it be “identified at each node” rather than “identified at each noted”?

We revised to “node”

Figure 1: “Aquaculture systems assessed with the Aquaculture Performance Indicators (n=69).” Rather than the ‘aquaculture systems’, the figure is a map showing the geographic distribution of the aquaculture systems assessed. Hence, a title along the line ‘Figure 1: Map showing geographic distribution of assessed aquaculture systems’ would better describe the figure.

We revised to “Geographic distribution of assessed aquaculture systems”

Text in Figure 5: In the graphic, you use ‘Community’ as one pillar of sustainability, a pillar elsewhere (including in the figure description) referred to as ‘social’. Changing it to ‘social’ would be consistent and make the graphic easier to understand.

Thank you for catching this. We replaced Community with Social.

Thank you for great comments that we find have significantly improved the paper. We hope you will find our responses satisfactory.

Major Comments

1. Conceptual overlap between predictors and outcomes (risk of circular inference)

A central conclusion of the paper is that aquaculture regulation is the most important cross-cutting factor explaining sustainability outcomes (e.g., Results section).

However, several environmental and social performance indicators appear conceptually linked to regulatory structures themselves (see Tables S1–S2). For example:

- environmental compliance,
- discharge control,
- antibiotic use,
- welfare practices,
- zoning and management,

are embedded in both performance outcomes and regulatory input metrics.

This creates a risk that the analysis partially measures:

systems scoring highly on regulation also scoring highly on metrics partly defined by regulation.

The manuscript should explicitly address this potential circularity and clarify:

- how independence between predictors and outcomes is ensured,
- whether overlapping constructs were tested for robustness,
- whether results hold after excluding regulation-adjacent outcome metrics.

Without this clarification, the central conclusion risks being tautological rather than explanatory.

2. Causal interpretation exceeds what the methods support

The manuscript frequently interprets variable importance from random forest models as evidence that certain factors *drive*, *contribute to*, or are *required for* sustainability outcomes.

However, random forests identify predictive associations, not causal mechanisms.

Several alternative explanations remain plausible, including:

- reverse causality (wealthier systems simultaneously achieve higher performance and stronger regulation),
- omitted institutional variables,
- shared underlying development gradients.

The authors should substantially moderate causal language and explicitly distinguish:

- predictive association,
- structural explanation,
- causal inference.

At minimum, discussion sections should acknowledge that results are consistent with institutional theory rather than definitive tests of it.

3. Limited theoretical advancement

The manuscript confirms a broadly established expectation within institutional economics and sustainability governance: that governance quality and regulation correlate with improved outcomes.

While empirical confirmation is valuable, the manuscript currently does not articulate a clear theoretical advance beyond existing literature.

The authors could strengthen the contribution by:

- proposing a mechanism explaining *why* regulation simultaneously aligns environmental, economic, and social outcomes,
- situating findings within debates on institutional complementarities or development pathways,
- clarifying whether aquaculture differs from fisheries or agriculture in systematic ways.

At present, the theoretical contribution feels implicit rather than explicit.

4. Sampling strategy limits generalizability

The dataset represents an opportunistic, non-random sample of aquaculture systems (Methods section). This is understandable given data constraints but has important implications.

Systems included are likely those with:

- available collaborators,
- institutional organization,
- measurable governance structures.

This may bias results toward more formalized sectors.

The manuscript should more clearly discuss:

- potential selection bias,
- limits to global inference,
- whether findings apply to informal or emerging aquaculture systems.

Currently, policy recommendations appear broader than the sampling design supports.

5. Measurement uncertainty is not addressed

API scores are derived partly from expert judgment, interviews, and proxy data. While vetting procedures are described, the manuscript does not quantify uncertainty arising from scoring decisions.

Possible improvements include:

- discussion of scorer variability,
- sensitivity tests,
- uncertainty ranges around aggregated scores.

Given that machine learning models are applied to constructed indices, uncertainty propagation becomes particularly important.

6. Interpretation of random forest importance metrics

Figure 2 presents variable importance based on permutation error increases. These values indicate predictive relevance but do not reveal:

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- but may worsen environmental outcomes under weak regulation.

This result has clear theoretical and policy relevance but is comparatively underemphasized relative to regulation importance claims.

I encourage the authors to elevate this interaction as a central contribution and expand its conceptual interpretation.

Minor Comments

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3. Some conclusions (e.g., "policy makers must expand the focus...") should be more carefully tied to empirical limits.
4. Consider adding a conceptual framework figure linking inputs → governance mechanisms → sustainability outcomes.
5. Clarify terminology consistency between "social," "community," and "societal" dimensions.

Strengths

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- Integration across environmental, economic, and social pillars.
- Clear writing and strong policy relevance.

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Recommendation

Major Revision

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With these improvements, the paper could make a meaningful contribution to sustainability and aquaculture governance literature.