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Evaluating the Impact of Ocean Acidification on Seafood – a Global Approach

Lamego [a,b*], F.

[a] Institute of Nuclear Engineering (IEN/CNEN), 21941-614, Rio de Janeiro, RJ, Brazil.
[b] Marine Biology and Coastal Environment Graduate Program (PBMAC/UFF), 24210201, Niteroi, RJ, Brazil

*Correspondence: Fernando.Lamego@ien.gov.br

Abstract: The quality of human life and food security are closely linked to the health of the ocean and the many goods and services it provides. However, the ocean is under cumulative stress from various human-driven pressures, leading to eutrophication, deoxygenation, loss of genetic biodiversity, contamination with emerging pollutants (e.g., microplastics and pesticides), and climate change (warming and ocean acidification). The effects of multiple ocean stressors and their interplay on marine life and ecosystems remain poorly understood. This underscores the urgent need for innovative science to resolve the complexity of the interplay of stressors and the resulting impacts. This paper reports findings from the Coordinated Research Project CRP K41018, a five-year program framed by the IAEA. The project was explicitly designed to advance Member States' understanding of both quantitative and qualitative impacts of ocean acidification on key economically relevant seafood species across different world regions. Furthermore, based on different sensitivity baselines across species, it aimed at exploring adaptation pathways for aquaculture and food industries. As a result, Member States would have improved their comprehension of resilience building in specific local contexts (e.g., types of environments, geographical parameters, human dimension). In this context, it is essential to look for ocean solutions to mitigate adverse impacts on seafood and support adaptation strategies based on nature that can counteract stressors. It is concluded that there is great synergy in planning integrated mitigation and adaptation strategies to multiple stressors in marine ecosystems.

Keywords: Multiple stressors, Food security, Adaptation, Mitigation.

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Avaliação do impacto da Acidificação do Oceano sobre os recursos pesqueiros: Uma abordagem global

Resumo: A qualidade da vida humana e a segurança alimentar estão intimamente ligadas à saúde do oceano e aos muitos bens e serviços que ele fornece. No entanto, o oceano está sob estresse cumulativo de várias pressões causadas pelo homem, levando à eutrofização, desoxigenação, perda de biodiversidade genética, contaminação com poluentes emergentes (por exemplo, microplásticos e pesticidas) e mudanças climáticas (aquecimento e acidificação do oceano). Os efeitos de múltiplos estressores oceânicos e sua interação na vida marinha e nos ecossistemas permanecem mal compreendidos. Consequentemente, há uma significativa falta de previsibilidade no uso de avaliações e padrões na gestão. Uma ciência inovadora é necessária para resolver a complexidade da interação de estressores e os impactos resultantes. Este artigo relata as descobertas do Projeto de Pesquisa Coordenada CRP K41018, um programa de cinco anos elaborado pela AIEA, que foi criado para promover a compreensão dos Estados-Membros sobre os impactos quantitativos e qualitativos da acidificação do oceano em espécies-chave de frutos do mar economicamente relevantes em diferentes regiões do mundo. Além disso, com base em diferentes linhas de base de sensibilidade entre espécies, o objetivo era explorar caminhos de adaptação para a aquicultura e as indústrias alimentícias. Como resultado, os Estados-Membros podem melhorar sua compreensão sobre a resiliência em contextos locais específicos (por exemplo, tipos de ambientes, parâmetros geográficos, dimensão humana). Nesse contexto, é essencial buscar soluções oceânicas para mitigar impactos adversos em frutos do mar e apoiar estratégias de adaptação baseadas na natureza que podem neutralizar estressores. Conclui-se que há grande sinergia no planejamento de estratégias integradas de mitigação e adaptação a múltiplos estressores em ecossistemas marinhos.

Palavras-chave: Múltiplos estressores, Segurança Alimentar, Adaptação, Mitigação.

1. INTRODUCTION

The consequences of ocean acidification (OA) on seafood production are already visible. In hatcheries located on the west coast of the US, a US$ 270 million industry, there has been a decline in the survival of oyster larvae since 2005, which appears to be connected to ocean acidification [1]. Similar consequences for seafood in other locations worldwide could be expected but are still unclear. Long-term experiments investigating the impacts of ocean acidification are rare. In a report on the economics of OA [2], it was recommended that research on high-value seafood be supported to enable socioeconomic assessment of impacts on food security (availability of good quality seafood).

In this context, the Coordinated Research Project CRP/IAEA entitled "Evaluating the Impact of Ocean Acidification on Seafood – a Global Approach" was expected to advance Member States' understanding of OA's quantitative and qualitative impacts on key economically relevant seafood species worldwide. Furthermore, based on different sensitivity baselines across species, it aimed at exploring adaptation pathways for aquaculture and food industries. As a result, Member States would have improved their comprehension of resilience building in specific local contexts (e.g., types of environments, geographical parameters, human dimension).

Despite several essential scale constraints – from the global-scale COVID-19 pandemic and economic hardships to organizational crises and personal issues –Member States managed to accomplish an impressive amount of relevant work in terms of data output, building local capacities, developing new research infrastructure, and improving methodologies, as well as disseminating knowledge to various stakeholders and raising the general profile of the topic of ocean acidification in the public sphere.

During the first coordination meeting held in Kristinberg, Sweden, in 2019, participants agreed on a protocol for a joined long-term experiment aiming at (i) evaluating the impact of ocean acidification on a local seafood species of economic and cultural importance, (ii) testing the potential for depuration period that could be implemented in aquaculture facilities to counteract the negative effects of ocean acidification. The overall scientific goals were to provide a local and global perspective on the impact of ocean acidification as a tool to promote global mitigation measures and local investment and adaptation strategies.

1.1. Ocean Acidification Research for Sustainability (OARS)

First, the Intergovernmental Oceanographic Commission of UNESCO hosted the first "Ocean in a High CO_2 World" Symposium in Paris in 2010. The UN 2030 Agenda was launched in 2015, with the Ocean Sustainable Development Goal (SDG 14) and Target 14.3: "Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels," were benchmarks. In 2017, global commitments to the ocean were signed. Finally, in 2021, the implementation of the United Nations Decade of Ocean Science for Sustainable Development was guided by the vision of "the science we need for the ocean we want." The global ocean acidification research community responded to the Ocean Decade call by co-designing a pioneering UN Decade program entitled "Ocean Acidification Research for Sustainability" (OARS) to deliver seven outcomes by the end of the Decade, which are based on a Theory of Change [3].

This article presents the main findings of the overall CRP and the framework of outcome#2 (Science to Action) for co-designing ocean acidification mitigation and adaptation strategies from local to global [4].

2. MATERIALS AND METHODS

Three scenarios were compared with true replicates per treatment to test our hypothesis. True replication requires that the carbonate chemistry be independently manipulated in each replicated aquarium (and not in header tank feeding aquariums). The three tested scenarios were:

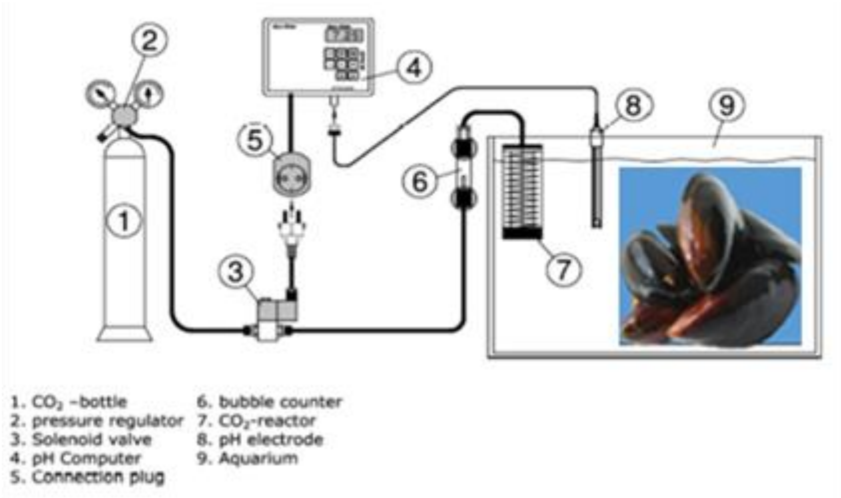
- High pH: control represents the present value of natural variability = 8,1 (Tanks 3A, 3B)

- Medium pH: the extreme of the present range of natural variability = 7.8 (Tanks 2A, 2B)

- Low pH: Δ pH of -0.3 from the extreme value (pH 7.8 – 0.3) = 7.5 (Tanks 1A,1B)

These three scenarios allowed us to test the influence of low pH in the context of present natural variability (phenotypic plasticity) and ocean acidification (stress response). Figure 1 shows the elements of the CO_2 manipulation system used for each replicate in the two acidified scenarios. The current pH (high scenario) was simulated by bubbling atmospheric air into tanks with compressors (pressure: 0.03MPa, air flow: 40 $L.min^{-1}$). A realistic amount of food should be provided to avoid additional stress and increased mortality, but it should not be ad libitum. Sampling and transportation to the laboratory were adapted to the tested species to minimize stress. The carbonate chemistry was manipulated after a few days of acclimation in breeding cages. A linear ramping decrease of pH over two weeks was adopted with rates of 0.04 and 0.02 per day for low and medium scenarios, respectively. Dead individuals observed during this acclimation period were replaced by another from the lab stock. Individuals were labeled with tags to follow individuals throughout the experiment. Mortality was evaluated by counting dead individuals in each tank throughout the experiment. Dead were counted and removed once a day. The mortality rate was calculated as the coefficient of the significant linear relationship between the number of living individuals and time, observed from the day before the first evidence of a dead individual in the aquarium. The individual growth rate was calculated as the coefficient of a significant relationship between time and size. The shape of the growth curve is dependent on the species. After three months, the survivors were transplanted to a mussel farm close to the site, where individuals were collected for acclimatation. The same parameters measured during the aquarium experiment were monitored for this in situ experiment. Sensory evaluation was performed at the end of the experiment, according to [5].

Figure 1: The CO_2 manipulation system automatically controls pH by continuously measuring it and activating the solenoid valve to inject CO_2 bubbles when necessary to adjust



To achieve transformative OA research by 2030, collaborative implementation of a co-designed vision is mandatory. The framework tracks the positive impacts and benefits according to the Theory of Change process, which are composed of 5 elements: (1) Inputs and Enablers (tools needed for resources and engagement); (2) Activities (*Modus operandi* and articulation with the target audience); (3) Outputs (Immediate effects from performed activities); (4) Outcomes (Changes generated in target audience) and (5) Impacts (Changes in society behavior). The main principles for OARS are: (a) focusing on the science, (b) building a solid leadership, (c) outcome-driven framework, (d) effective communication, and (e) performance evaluation. It will inform decision-makers about practical fisheries and aquaculture resilience strategies, well-informed ecosystem restoration and conservation choices, blue carbon project evaluations, nature-based solutions, marine carbon dioxide removal (mCDR) strategies, promotion of pollution controls, marine spatial planning, and marine management.

3. RESULTS AND DISCUSSIONS

Thirteen countries were planning an experiment back in 2019, investigating the impact of low pH on a total of 14 different seafood species: (i) 10 mollusks, (ii) 1 crustacean, (iii) 1 echinoderm, and two fish (Table 1). Data on the local variability in the carbonate chemistry at the sampling site were available or collected in 10 of the 13 countries and allowed to design experiments with appropriate pH scenarios. Eleven countries could perform experiments on a total of 13 seafood species. Due to practical and unforeseen constraints (see below), not all participants could follow the agreed protocol and adapt the design to the circumstances (e.g., limited access to the facilities, high mortality in the controls, water quality, etc.). All the countries that performed an experiment followed the agreed design set of measurements (carbonate chemistry, mortality, growth) except for the sensory evaluation that could only be performed in 3 countries (Brazil, Costa Rica, Ecuador). Table 1 shows the species chosen by each country that performs experiments and monitors carbonate.

All participants considered that their learning outcomes from the CRP experience were very high (5 out of 5 on a scale from 1 to 5), while the benefits to their countries were ranked as high (4.2 out of 5). All participants agreed that this CRP project allowed them to build the capacity to perform ocean acidification experiments in their country. However, some participants faced significant experimental challenges, including access to seawater (4 out of 9 participants), easy access to a source of food for their model seafood species (3 out of 9 participants), or lack of local technical support (4 out of 9 participants). A substantial constraint was the lack of previous expertise in culturing the seafood species of choice (5 out of 9 participants). These factors limited the ability of some participants to maintain the organisms for an extended period (7 out of 9 participants) and provide the ability to evaluate the number of organisms to add to their experimental unit (e.g., 4 participants could not perform the sensory evaluation due to the lack of material at the end of the exposure).

Participants shared the many challenges faced during the experiments, from space and power supply to water quality and availability of food for animals. The project chair referred to another similar experiment, reuniting institutions from several Member States, in which consistent efforts were made to ensure optimal experimental conditions.

Table 1: Contribution of the participating countries to the global experiment

HEAD	Species	Latin Name	Experiment	Carbonate
Argentina	Patagonian scallop	*Zygochlamys patagonica*	Yes	Yes
Bahamas	Queen Conch	*Aliger gigas*	Yes	No
Brazil	Mussel	*Perna perna*	Yes	Yes
Costa Rica	Spotted rose snapper	*Lutjanus guttatus*	Yes	Yes
Cuba	Shrimp	*Litopenaeus vannamei*	No	Yes
Ecuador	Shrimp	*Litopenaeus vannamei*	Yes	Yes
Egypt	Clam	*Ruditapes decusatus*	Yes	Yes
Kenya	Mud whelk Cockles Sea cucumber	*Telebraria palustris* *Anadara antiquatia* *Holothuria arenacava*	Yes	Yes
Lebanon	Fish	*Siganus rivulatus*	No	Yes
Mexico	Abalone Aballone	*Halliotis fulgens* *H. rufescens*	Yes	Yes
Morocco	Mussel	*Mytilus edulis*	Yes	No
Thailand	Mussel	*Perna viridis*	Yes	No
Türkiye	Mussel	*Mytilus galloprovincialis*	Yes	Yes

Coordinators periodically gathered participants to analyze difficulties and support a smoother way forward; they discussed best practices in experimental set-up and maintenance, e.g., which foods better support organisms' vital functions and development or what kind of protocol is necessary to monitor and maintain appropriate water physicochemical parameters. The difference was that they worked on the same species, while this CRP's goal was to have researchers work on species of particular relevance to their countries' populations and economies, which made it difficult to establish uniform laboratory aquaculture protocols. As a lesson learned, the group mentioned the need for alternative routes for future experiments.

The working group of Outcome#2 from OARS drew a mapping exercise to identify potentially relevant information for decision-making at different spatial scales with emphasis on (1) the sensitivity of critical species to ocean acidification and potential response strategies, (2) the relevance of land-based activities and interactions; (3) the role of coastal habitats to mitigation and remediation of ocean acidification; (4) relevance of OA information to the management of water quality (indicators); (5) relevance of OA information to evaluate blue carbon and mCDR; (6) reinforce policies to mitigation of CO_2 emissions. Table 2 shows the main categories proposed by OARS to outline the critical information needed for decision-making, providing a framework for mitigation and adaptation actions to guide policymakers and other stakeholders [6].

Table 2: Framework for identifying target OA information needs for mitigation and adaptation actions.

Category	Action	Type
Impact of GHG emissions on global health	Reduce CO_2 emissions	Mitigation
	Climate risk policy and funds	Adaptation
Food security and resilience of blue economy	Fisheries and aquaculture management	Adaptation
Management tools to protect and restore	Marine Spatial Planning and Protected Areas	Adaptation
Blue carbon sequestration projects	Support carbon sequestration goals	Mitigation
	Guide nature-based solutions	Remediation
Local projects to reduce land-based pollution	Identify OA hot spots to reduce human pressure	Mitigation
Risks and benefits of different mCDR strategies	Baselines and OA connections Pros and Cons of each strategy	Mitigation

4. CONCLUSIONS

Despite the extraordinary constraints, the benefits for the CRP participants and their respective countries included increased capabilities to perform marine experimental research, implement best practices for ocean acidification experiments and observations, and improve national and international collaborations.

The group agreed that this CRP was the first step toward a better understanding of ocean acidification's impact on seafood. It also highlighted the importance of continuing this work. It considered new avenues, including resolving the impact of ocean acidification in the context of environmental variability and multiple stressors, its indirect effects through ecological feedback, and the test and implementation of adaptation solutions.

To increase the probability of success of future similar programs, participants shared some potential solutions:

- work in close collaborations with an expert in culturing the selected species and at facilities where these species are cultured (e.g., aquaculture);
- provide some alternative model species with a long history to be cultured in the laboratory, and training on how to handle them for the participants who do not have access to advanced infrastructures or easy access to seawater or natural food for their organisms;
- establish multiple protocols with different levels of complexity, allowing the test of the same questions under different foreseeable and unforeseeable circumstances;
- maintain strong communication between participants throughout the project to collectively solve issues.

Participants exchanged ideas about the potential for future collaborations between projects and institutions beyond the end of the CRP project cycle and their respective needs concerning data and publications. The possibility of co-designing a new CRP was discussed.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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