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Original Research Article

University-Industry-Government Integration in the Development of Sustainable and Cost-Efficient Solutions for the Shrimp Sector in Colombia: Nutriaqua Case

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ABSTRACT

This paper presents a case study, and lessons learned that illustrates the development of a cost-efficient and sustainable solution for shrimp farming sector in Colombia, using the model of Technology Readiness Level with stages from 1 to 9, and analizing the the participation and linkage of quadruple helix actors. The focus was on the development of this product considering that feeding and fattening represents approximately 40% of production costs. The solution was designed in a sustainable way, using local raw materials, resulting in a significant reduction in water and energy consumption during the process. This involved local communities and small producers, as well as shrimp and feed-producing companies, making possible to address multidimensional challenges and leverage diverse knowledge to optimize the solution. An iterative process of tests and improvements was carried out, validating its efficiency and feasibility in real conditions. The participation of the quadruple helix guaranteed a comprehensive vision and effective adaptation to meet the needs of producers. The result was the creation of a spin-off, a technology-based company which allows the effective transfer of technology and knowledge, facilitating the widespread adoption of the solution in the shrimp farming industry.

KEYWORDS

Spin off, Technology Readiness Level, product design, University-Government collaboration.

HIGHLIGHTS

- Early stakeholder engagement is key to bridging research and industry in sustainable aquaculture.
- Diversified funding and policy support are crucial to overcoming the "Valley of Death" in innovation.
- Business and financial skills are essential for commercializing scientific research.
- Long-term policies must replace short-term funding to scale sustainable technologies.

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INTRODUCTION

Seafood serves as a crucial source of nutrition and significantly contributes to food security worldwide, particularly in developing countries, where it not only provides essential nutrients but also supports livelihoods and economic development [1].To meet the growing demand for seafood, aquaculture has become the world's fastest-expanding food production sector [2]. However, this rapid expansion brings critical sustainability challenges, particularly concerning resource efficiency and environmental impacts [3], requiring innovations that decouple industry growth from increasing pressure on natural resources [4].

Among aquaculture sectors, shrimp farming dominates the industry, accounting for approximately 65.3% of total production in the crustacean sub-sector [5]. Despite its economic and nutritional significance, shrimp aquaculture faces urgent challenges related to feed sustainability, environmental degradation, and resource consumption [6], [7]. Traditional shrimp feeds rely heavily on fishmeal and fish oil derived from wild fish stocks, contributing to overfishing and ecosystem degradation [8]. Thus, achieving sustainable growth requires solutions that enhance production efficiency, reduce environmental footprints, and integrate more resource-efficient and circular production models [9].

This sector is deeply interconnected with the Sustainable Development Goals (SDGs), particularly those addressing food security, sustainable consumption and production, and climate action [10]. However, shrimp aquaculture carries significant environmental externalities, including high water and energy consumption, greenhouse gas emissions, eutrophication, and degradation of aquatic ecosystems [11]. These impacts underscore the need for sustainable innovations in feed production, disease management, and climate resilience to ensure long-term viability [12].

One of the most promising research areas in sustainable aquaculture has been the development of alternative protein sources to reduce reliance on marine resources and impact on the overall sustainability of the value chain [13]. Various alternatives have been proposed, including plant-based meals and insect-based feeds [14]. However, despite significant progress in this sector, history has shown that technological advances face issues with large-scale commercial adoption of these innovations which often remains limited due to social, technological, regulatory, and market barriers [15], making aquaculture one of the slowest sectors to adopt new technologies, even when they offer clear sustainability and profitability improvements [16].

Beyond environmental considerations, socioeconomic factors also play a key role in the sustainability of shrimp aquaculture [17]. Rising operational costs, increasing regulatory demands, and shifting market expectations towards low-impact, traceable products challenge the industry's resilience [18]. Achieving a sustainable transition requires collaborative efforts across academia, industry, government, and local communities to develop scalable, knowledge-driven solutions [19]. This quadruple helix approach is essential to bridge the gap between research and industry implementation, facilitating technology transfer and adoption of sustainable innovations[15], [19].

This study examines the case of Nutriaqua, a university spin-off developed to commercialize Biocam, an alternative shrimp feed designed to reduce environmental impacts and enhance economic sustainability in aquaculture. For over 30 years, independent researchers in Barranquilla, Colombia, have worked on developing sustainable feed solutions for shrimp farming. However, the realization of their impact only became evident when stakeholders from the quadruple helix model collaborated to accelerate the process of technology transfer, adaptation, and adoption.

To do so, it employs a case study to analyze the Technology Readiness Levels (TRL) of Biocam, mapping its development from research to commercialization and it also evaluates the role of different stakeholders (academia, industry, government, and communities) in shaping the innovation process, emphasizing sustainability, knowledge-based economic growth, and policy integration.

As highlighted by Kolde & Wagner [20], multi-stakeholder engagement is essential in addressing structural challenges in traditional industries, and in aquaculture, it has been noted that this engagement contributes with sustainable management of the productive activities [21]. Similarly, this paper underscores the importance of inclusive policies and cross-sectoral collaboration in facilitating a sustainable transition within shrimp aquaculture. In both cases, the participation of different stakeholders plays a pivotal role in ensuring that sustainability efforts translate into long-term economic and social benefits [22].

By analyzing this case, the study aims to extract key lessons for sustainable technology development and transfer, providing insights that could guide future initiatives in sustainable aquaculture, food production systems, and circular economy practices. These findings contribute directly to discussions on innovation-driven sustainability, resource efficiency, and environmental impact reduction. The structure of this work is outlined as follows: the first section presents Materials and methods, followed by an analysis of Biocam's development across TRL stages and the role of stakeholders in shaping its commercialization. Finally, this paper contrasts the findings with existing literature, offering and overview of strategic recommendations to strengthen sustainable innovation and accelerate technology transfer in aquaculture.

MATERIALS AND METHODS

Given the slow adoption of new technologies in aquaculture [16], often hindered by regulatory constraints, market resistance, and production scalability challenges, understanding the factors that drive, or hinder technology transfer is crucial. This study aims to identify, analyze, and document key lessons from the development of Biocam, from its conceptualization to the establishment of Nutriaqua, a university spin-off designed to facilitate the transfer of this innovative feed technology to shrimp producers.

To achieve this, this research examines Biocam's evolution through the Technology Readiness Level (TRL) framework [23], assessing the role of academia, industry, government, and communities in bridging the gap between research and commercialization, exploring how structured collaboration among stakeholders fosters sustainable innovation [24], helping overcome the industry's reliance on conventional feed sources that contribute to environmental degradation [13].

The significance of these lessons lies in how they contribute essential insights into the dynamics of collaboration among universities, businesses, governments, and communities as active participants in research and development processes. These collaborations have the potential to generate sustainable alternatives that enhance the positive outcomes of aquacultural activities while minimizing their negative impacts, successfully addressing the sector's challenges. The methods and process are outlined in Figure 1 and further detailed below.

The research began with a literature review to outline the timeline and evolution of the Biocam solution, from its conceptualization to the commercial exploitation of the supporting patent by the university spin-off. This development was further analyzed through the lens of TRL's [23], and the contribution of stakeholders within the quadruple helix innovation system, aiming to understand their impact on the product's development, the company's establishment, and the transfer of results and contributions of associated projects in reducing negative economic, social, and environmental impacts.

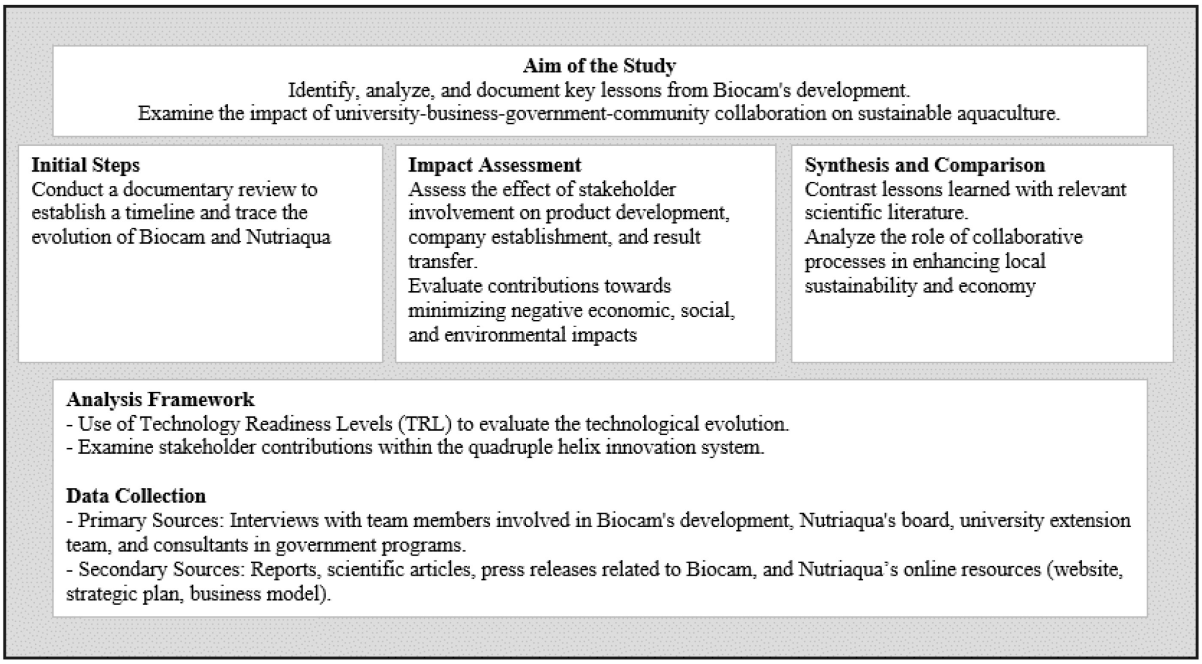


Figure 1 Materials and Methods.

Primary sources included interviews with members of the teams involved in the development of Biocam and the board of directors of NUTRIAQUA, the university extension team at Universidad del Atlántico, and individuals assisting in consulting and business development projects under government programs. Secondary sources comprise reports, scientific articles, press releases related to Biocam, and Nutriaqua's website, strategic plan, and business model.

Finally, these lessons were juxtaposed with relevant scientific literature on the topic, exploring the contribution of these collaborative processes to the sustainability of territories and the local economy. This approach not only highlights the practical applications of case study research but also eliminates redundancies, focusing on the synergistic relationship between academic knowledge and practical application for sustainable development.

RESULTS AND DISCUSSION

The results of this study provide a comprehensive overview of the development and validation of Biocam, a sustainable alternative for shrimp aquaculture. The analysis follows the Technology Readiness Levels (TRL) framework, evaluating key stages from conceptualization to commercial deployment. This approach aligns with previous studies that highlight the importance of systematic innovation assessment in aquaculture, particularly in optimizing feed formulations and reducing environmental impacts [14], [25]. The findings emphasize the role of stakeholder engagement in overcoming challenges related to funding, adoption, and market readiness. By integrating technological, environmental, and economic perspectives, this research contributes to the broader discussion on sustainable aquaculture development and its potential applications in emerging markets.

Biocam and Nutriaqua context

To meet the nutritional and fertilization needs of shrimp while addressing the environmental challenges of aquaculture, Pharmaceutical Chemist JOSE LUIS SANTAMARIA MARTINEZ developed Biocam between 1987 and 1991. Using his own resources, Martinez created a natural food formula for aquatic microorganisms in high salinity crustacean farms. The product underwent testing on 30 hectares of white shrimp (Litopenaeus vannamei) cultivation in Cartagena, receiving positive feedback from the Bolívar shrimp sector after 80 tons were used in trials. This product allowed to considerate the effects of feeding practices and products to support the sustainable management of a shrimp farm, which is a relevant aspect of the sustainability of the aquaculture challenges [25].

The first development phase in 2006 at Arroyo de Piedra, Luruaco/Atlántico, saw Biocam's application in 10,000m² shrimp pools, yielding shrimps of 14cm in size and 14g in weight from a 250,000 post-larvae plantation. Composed of agro-industrial and marine fossil wastes, Biocam was essential for the shrimp's primary biological cycle. In 2008, the second phase took place at San Martín farm, Repelón/Atlántico, alongside Soluciones San Martín LTDA and Universidad del Atlántico. This phase involved three 1-hectare pools with 300,000 post-larvae each, where Biocam and commercial feed were combined, supporting healthy microorganism development, and achieving shrimp sizes of 14 to 16 cm and weights of 14 to 16g in 110 days which is higher compared with traditional diets [26].

From 2014 to 2015, the third phase at the Gallito shrimp farm in Repelón, under COLCIENCIAS and the University's initiative, utilized five one-hectare pools with 300,000 post-larvae each. This phase saw shrimp reaching 14 to 16 cm and 14 to 16g in weight by 100 days, with Biocam application leading to significant feed savings and a patent (WO2017195167A1) for its sustainable approach. The fourth phase began in 2019, aiming for commercial deployment and product development with support from Minciencias, Universidad del Atlántico, and other partners. This led to the formal establishment of Nutriaqua. Despite delays due to the pandemic, this phase marked a transition to commercialization, with legal recognition for the company NUTRIAQUA in 2023 and the start of commercial activities in 2024, showcasing a strategic shift from R&D to market introduction.

First Development Phase of Biocam: Addressing Stages 1-3 and Aquaculture Challenges

TRLs serve as a structured measurement system that aids in evaluating the maturity level of a specific technology, enabling uniform comparisons of maturity across various technology types and is useful in aquaculture to support natural resource management and conservation [27]. This model consists of nine levels depending upon the stage of development of the technology [28]. The first three stages correspond to the research stage where basic principles are observed, the technology concept is formulated and there is an analytical or experimental proof of concept as shown in Figure 2.

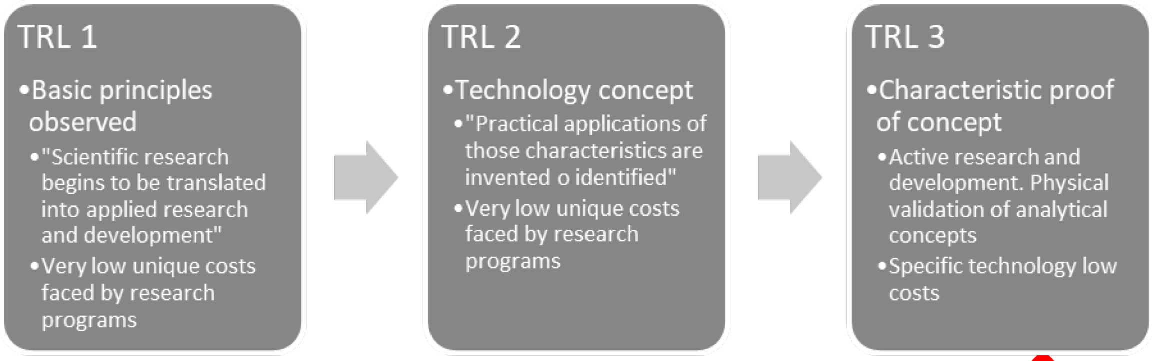


Figure 2. Stages 1-3 in TRL Model. Source: Adapted from [28]

The initial development phase of Biocam intricately navigated during the first 19 years of the development of the product the first three stages of the TRL model, focusing on the foundational observation of basic principles. This phase was characterized by the pioneering efforts of the lead researcher, who engaged in informal discussions and processes with small-scale shrimp producers and entrepreneurs. These interactions, grounded in the context of personal friendship and individual relational capital, highlighted the collaborative yet challenging nature of early-stage innovation.

The implication and participation of the producers in these early stages helped to develop a comprehensive approach and delimitation of the problem faced in the sector. A problem apparently related to production costs but deeply related to sustainability issues, where the involvement of the stakeholders plays a key role to develop solutions to improve the social, economic, and environmental challenges [29]. The problems faced by stakeholders must be transformed into quantifiable metrics and solutions that are designed to respond to inquiries from management, thereby guiding them toward making appropriate investment decisions [30].

Operating at the personal risk of the inventor and relying on private funding, this phase encountered significant hurdles, primarily due to limited access to resources. Despite these obstacles, the collaboration between the researcher and the productive sector stakeholders led to the concrete formulation of a concept addressing both economic and environmental challenges in the aquaculture sector. The identified need was for a nutritional solution capable of reducing feed costs or at least mitigating the rising prices due to reliance on imported inputs.

Main lessons of phase 1: The early development of Biocam was driven by the pressing challenges faced by the aquaculture sector, particularly the need for efficient water use, enhanced larval growth, improved productivity, and cost reduction in shrimp farming, problems that are still present in industry [5].

These challenges align with broader industry concerns about sustainability and resource efficiency, as highlighted in previous studies on sustainable aquaculture practices [14], [31] so, facing these challenges early, aims for the development of integral solutions. The foundational work carried out during the research phase set the groundwork for addressing these challenges through cost-effective, innovative feed formulations, and environmentally conscious production strategies, as illustrated in Figure 3.

A key lesson from this phase was the critical role of stakeholder involvement in problem definition and solution conceptualization [32]. The traditional TRL model puts the costs and risk only in the hands of the research team, but experience showed that early involvement of stakeholders was key into defining a sustainable solution. However, while industry and academic stakeholders contributed significantly to framing the challenge, the lack of financial commitment from these same actors proved to be the primary barrier to the progression and scalability of the Biocam project.

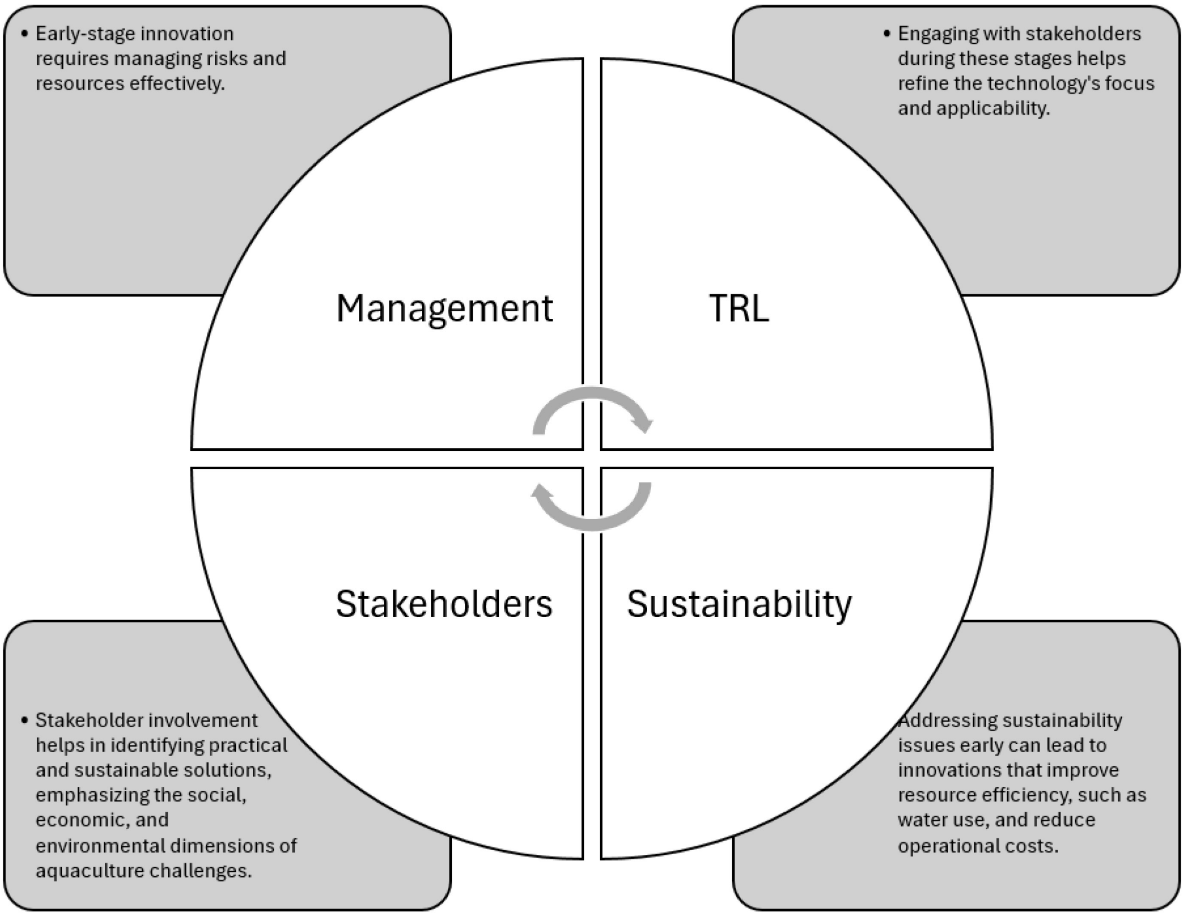


Figure 3. Lessons learned in the "Research" Stage

This aligns with existing literature, which emphasizes that limited financial backing and risk aversion among stakeholders frequently hinder the transition from research to large-scale implementation [33]. Securing early-stage investment is essential to ensure that innovative solutions not only emerge but are also systematically tested, refined, and adapted for commercialization [34]. Effective stakeholder engagement strategies, which highlight the economic and environmental benefits of investing in sustainable feed solutions and government involvement, are needed at these stages because they are crucial for overcoming social and financial barriers and fostering long-term adoption of sustainable technologies.

Second Development Phase of Biocam: Progressing through Levels 4-6

In this stage, the University became a significantly involved actor in the project, using internal resources to advance the development of formulation. This advancement included both laboratory validation and field trials in productive environments, marking a crucial transition to the development phase of the TRL model, encompassing levels 4 to 6. This stage is characterized by the formal documentation and validation of the product's effectiveness and its economic and environmental impacts on the industry as shown in Figure 4.

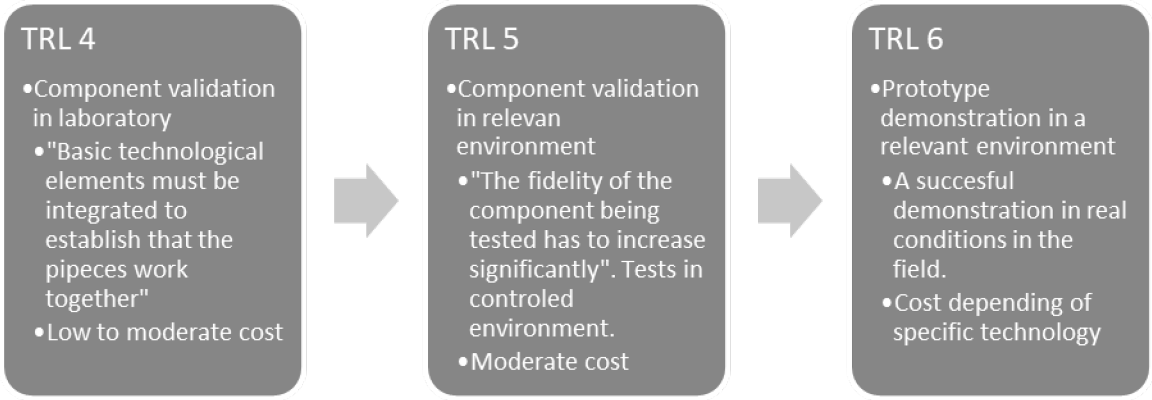


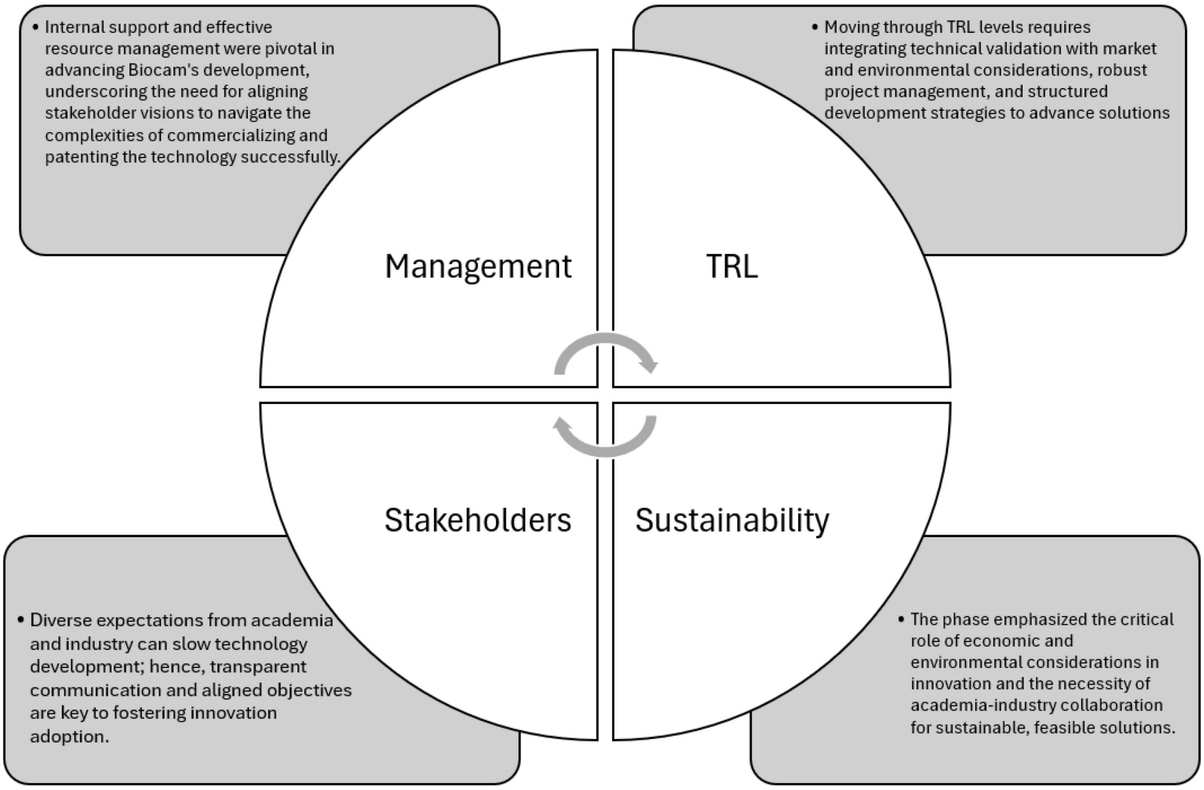
Figure 4. Stages 4-6 in TRL Model. Source: Adapted from [28]

A key aspect of this phase was the collaboration between academic and industry sectors, which enabled access to external financing for product development and field testing according to the theory of the four key societal aspects for the deployment of technology: impact on the environment, stakeholders' involvement, policy and regulations and market and resources [35]. Despite no substantial changes in the product's characteristics and functionality, the focus was on formally documenting and evidencing results through technical trials within formulated projects.

Interviews with stakeholders involved revealed challenges in product development progression, largely due to the specific visions of the actors. Companies, recognizing the potential solution to their production issues, expected the product to be fully subsidized which is a behavior in line with the idea of universities as a source of cheap resources for industry [36]. They acknowledged the product's quality but showed no intention to purchase, requesting more projects to continue receiving the input. From the academic perspective, the focus was on the potential of product development to generate new projects and publications, maintaining the research groups' status [37]. This limited productive vision in this phase hindered the advancement of the first patent attempt for the developed technology.

Main lessons of phase 2: As Shown in Figure 5, the second development phase of Biocam offers insightful lessons on navigating the complex interplay between academia, industry, and the pursuit of sustainable solutions within the aquaculture sector. A pivotal takeaway from this phase is the critical need for alignment among stakeholders' visions and expectations, emphasizing the significance of integrated management principles in technology development [24]. The University involvement, utilizing internal resources for laboratory validation and field trials, underscores the utility of the TRL model as a framework for advancing from conceptual to developmental stages (levels 4 to 6) [23]. This progression is vital for validating the product's effectiveness and its socio-economic and environmental benefits, adhering to principles of sustainability theory [38].

However, stakeholder theory in practice revealed friction points, particularly in reconciling the diverse objectives of the academic and industrial sectors. The expectation of companies for fully subsidized solutions, despite recognizing the product's quality, alongside academia's focus on leveraging product development for further research and publications, presented challenges in advancing towards commercialization and patenting the technology where many research products fail, entering in the valley of death [15]. This scenario highlights the necessity of fostering a shared understanding and commitment to commercial viability and sustainability goals among all parties.



. Lessons learned in the "Development" Stage

Therefore, navigating the TRL framework successfully requires not only technical and scientific rigor but also strategic stakeholder engagement and management to ensure that innovative solutions can achieve their full potential in contributing to sustainable aquaculture.

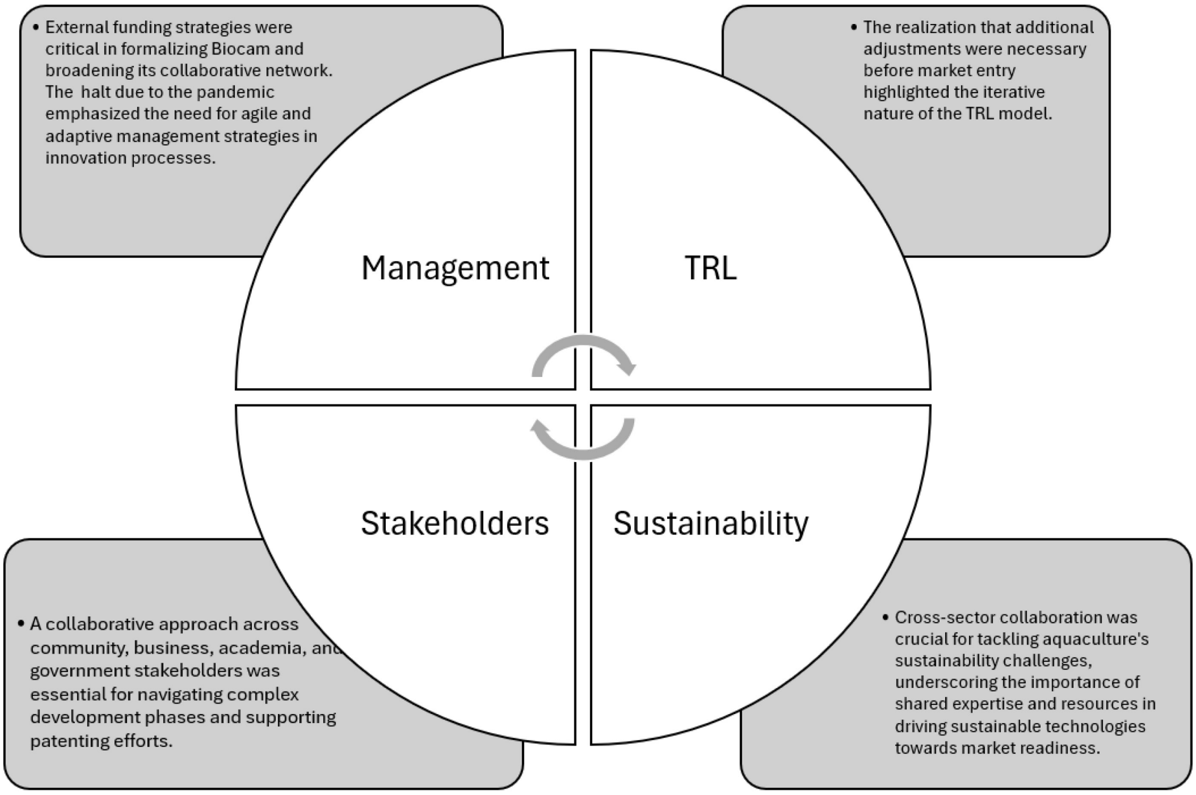
Third development phase: Deployment and Level 7

In the third phase of the development of Biocam, the employment of external funding strategies was instrumental in formalizing the product and broadening its collaborative network. From 2015 onwards, significant new partners, including "Cientech," a research results transfer office, and "Olarte Moure," a law firm specializing in patent processes, were integrated into the development process. This phase was marked by the essential integration of knowledge across different domains: community and business stakeholders contributed product requirements, academia provided technical and scientific expertise, the government acted as a catalyst and supported patenting costs, and interface agencies facilitated previously challenging transfer and protection mechanisms. The convergence of government, producers and academy was a key aspect of innovation [37], and the involvement of these actors provides a collaboration framework that "maximizes the usage of resources and knowledge in the organizations and considerably benefits them in a variety of aspects" [39].

This collaborative approach was crucial for navigating the deployment phase of the TRL model, achieving level 7 which is characterized by the actual prototype demonstration in real productive field tests [28]. It led to the formulation of a patent that, while offering protection and proving the innovation's novelty, indicated that further adjustments were necessary for market entry, because technology transfer goes beyond the mere invention [40]. The product's development paused until the pandemic began in 2020, illustrating the dynamic nature of innovation processes and the importance of cross-sector collaboration for addressing the environmental and sustainability challenges [41].

The importance of this stage lies in the context of the theory: The "Valley of Death" is a moment in technology development that typically spans from TRL-4 to TRL-7 [15], highlighting the critical need to incorporate Investor Relations to build a structural bridge in an scenario where the absence of investors means the absence of a solution, and without strong relationships, sustainability is unattainable. Here it is important to address information asymmetries to maintain effective stakeholders' relations [42]. This stage underscores the value of combining diverse expertise and resources to advance sustainable technologies, highlighting the continuous journey towards market readiness and the iterative nature of technological innovation.

Main lessons of the phase 3: The third phase of Biocam offers rich insights into the integration of diverse management and theoretical perspectives, driving the project towards achieving a significant milestone in the TRL model. The utilization of external funding strategies was pivotal, not only in formalizing Biocam but also in expanding its collaborative framework. Figure 4 shows the lessons learned during this stage.



. Lessons learned in the first step of the "Deployment" Stage

The inclusion of new partners underscores the importance of multidisciplinary collaboration in the innovation process, aligning with stakeholder theory by engaging various contributors from community, business, academia, and government sectors [39]. Each stakeholder group played a distinct role, from defining product requirements and providing scientific expertise to acting as a catalyst for development and supporting legal and patenting efforts.

This phase illustrates, as shown in Figure 6, the critical management principle of leveraging external resources and partnerships to overcome development and commercialization challenges, reflecting TRL theory by successfully navigating through the deployment phase to achieve TRL 7. However, the realization that the patent, while a significant achievement, required further refinement for market entry, emphasizes sustainability theory's call for continuous improvement and adaptation in product development [40]. The pause in development due to the pandemic further highlights the unpredictable nature of innovation processes and reinforces the necessity of resilience and flexibility in management strategies.

Fourth development phase of Biocam: Nutriaqua SAS. Levels 8 & 9

In Technology Readiness Levels (TRL), stages 8 and 9 represent the final phases before full commercial deployment. TRL 8 corresponds to the completion and validation of the actual system in its operational environment, ensuring that it meets all performance, safety, and regulatory requirements. At this stage, the technology undergoes rigorous testing under real-world conditions, confirming its functionality, reliability, and readiness for market introduction. TRL 9 signifies the fully operational system, demonstrating proven performance in its intended environment. This phase marks the transition from innovation to full-scale production and commercialization, indicating that the technology is mature and ready for widespread adoption [28].

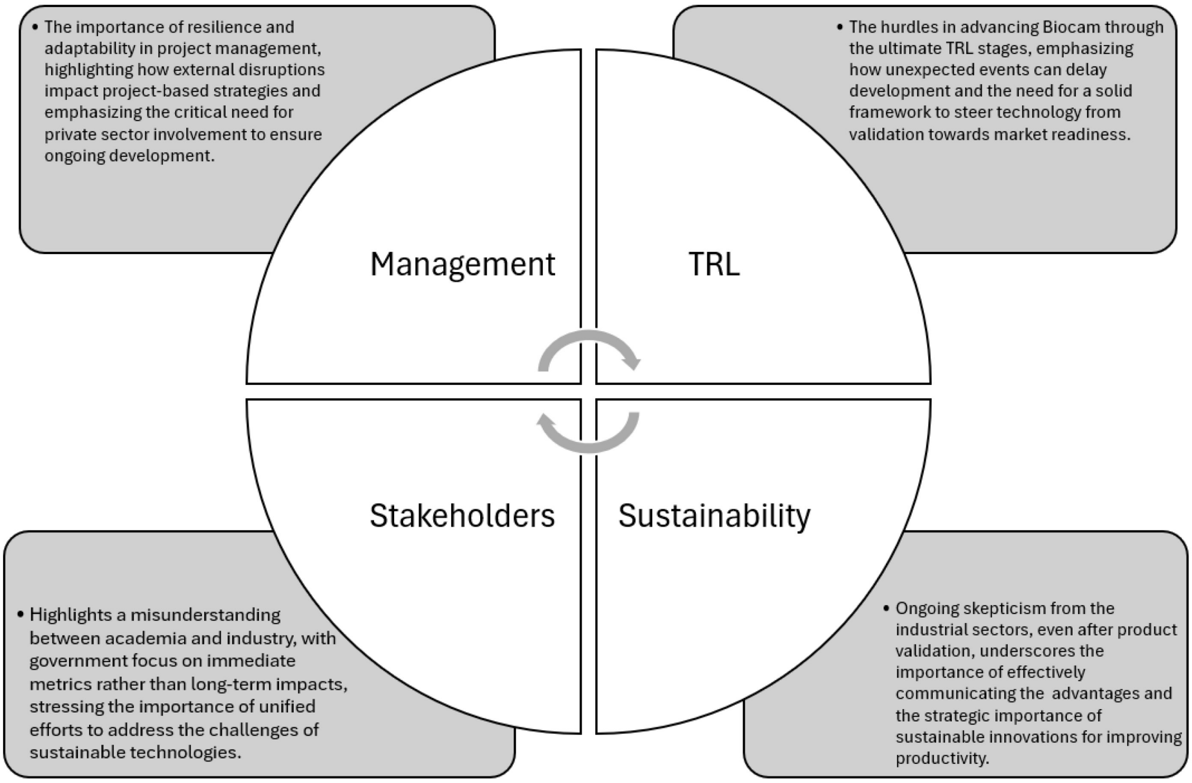
In 2020, a proposal funded by the National Ministry of Sciences (Minciencias) aimed to advance Biocam to the final stages of development under the TRL model encountered substantial delays due to the pandemic and a governmental change, impacting the work schedule. This situation highlighted that while project-based strategies facilitate funding, they are susceptible to external events, indicating a need for private actions and efforts at this stage of development.

Interviews revealed persistent skepticism within the industrial and productive sectors regarding the product, despite its technical development and validation. The commitment to investing in Biocam as a strategic decision for productivity enhancement remained uncertain, with lingering doubts about the academic sector's ability to produce industrial-grade inputs. On the university side, despite having a validated business model, concerns were raised about the research team's capacity to shift from an academic to a business-oriented profile, despite having professionals in these areas. This suggests a perceived divide between researchers and administrators.

From the perspective of the government and support entities, the focus has largely been on project execution without in-depth follow-up on broader impacts beyond management indicators, potentially limiting their role as catalysts without a business development vision. This fourth phase and the establishment of Nutriaqua as a Spin-off underscores the complexities of transitioning from R&D to market introduction, highlighting the importance of aligning expectations and capabilities across the academic, business, and governmental spheres to overcome challenges in sustainable aquaculture innovation.

Main lessons of the phase 4: The fourth phase, marked by its progression towards the final stages of the TRL model, brought to light several critical lessons within the domains of management principles, TRL, sustainability, and stakeholder theory as shown in Figure 7.

The experience of navigating delays due to unforeseen external factors, such as the pandemic and governmental changes, underscores the vulnerability of project-based strategies to external shocks. This vulnerability signals the growing importance of private initiative and resilience in the later stages of technological development, emphasizing the need for adaptable and robust management practices.



. Lessons learned in the last levels of the "Deployment" Stage

Persistent skepticism from the industrial and productive sectors, despite the technical validation of Biocam, highlights a gap in perception and trust between academia and industry [39]. This points to a broader challenge in stakeholder theory: building confidence in the academic sector's ability to produce viable industrial inputs and making the case for such innovations as strategic investments for enhancing productivity [30]. The hesitancy to invest reflects a critical barrier to transitioning from research and development to practical, market-driven applications mainly for cultural differences and language between institutions [43].

Furthermore, the concerns about the research team's ability to transition from an academic focus to a business-oriented approach reveal a crucial aspect of management theory: the necessity of cultivating business acumen within research teams to bridge the gap between innovation and commercialization [44]. This transition is not merely about changing individual roles but about fostering a culture that values entrepreneurial thinking alongside scientific excellence. From the government and support entities' standpoint, the emphasis on project execution without substantial follow-up on the broader impacts illustrates a missed opportunity in sustainability theory and support for Small and Medium Enterprises (SMEs) [45]. Effective governance and support mechanisms should extend beyond facilitating project milestones to nurturing a sustainable ecosystem that aligns with broader environmental and social goals. The role of government as a catalyst in this context is not only about funding but also about fostering a vision for sustainable business development that can drive the aquaculture sector forward.

CONCLUSION(S)

The development and commercialization of Biocam represents a paradigmatic case study of sustainable innovation in aquaculture, offering lessons that extend beyond its specific context. The Technology Readiness Level (TRL) model, stakeholder engagement, and sustainability challenges are central to understanding the evolution of Biocam from an experimental concept to a market-ready product. This case highlights the critical interplay between academia, industry, government, and funding agencies in advancing sustainable aquaculture solutions [25].

Firstly, one of the most striking insights from Biocam's development is the necessity of adaptability and resilience when navigating complex, multi-stakeholder technological development processes. The impact of external disruptions—such as pandemics and governmental changes—demonstrates the fragility of project-based funding mechanisms, which can delay or halt innovation progress [15]. This underscores the importance of strategic foresight and risk management, ensuring that sustainable innovations are not solely reliant on external conditions but also bolstered by private investments and diversified funding strategies [42]. The study illustrates the significance of clear communication and alignment among stakeholders, particularly between academia and industry, in transitioning sustainable innovations from validation to market readiness [24].

Persistent skepticism from the industrial sector, despite technical validation, emphasizes the need for effectively communicating the strategic value and sustainability benefits of innovations, underlining the importance of bridging the comprehension gap between scientific research and industrial application [39]. This reflects broader issues within sustainable technology transfer, where research teams often prioritize scientific rigor, while industrial stakeholders emphasize immediate economic returns and risk mitigation.

Moreover, the case study of Biocam reveals the essential role of government and support entities not just as funders but as catalysts for long-term development impact; there is a need to support R&D and expert training and development of policies to accompany small enterprises to support SMEs in the context of uncertainty [45]. The focus on short-term project execution metrics, as opposed to long-term sustainability impacts, suggests a need for governmental and supporting bodies to broaden their roles in fostering a conducive environment for the commercialization of sustainable technologies.

The delays experienced in the later TRL stages highlight the risks associated with over-reliance on governmental funding and the need for more integrated public-private collaboration models. Governments must act not just as funders but as enablers of an innovation ecosystem, fostering long-term resilience by facilitating policy continuity, investor confidence, and ecosystem stability [45].

A crucial challenge in stakeholder theory is the difficulty in translating academic innovations into commercially viable solutions. Companies viewed university-led projects as subsidized sources of technological advancements rather than market-driven products. This aligns with existing literature on the "valley of death" phenomenon, which highlights that many technologies fail between TRL 4 and TRL 7 due to financial and market uncertainties [15]. The lack of early-stage financial commitments from industrial stakeholders suggests the need for new engagement models where companies share developmental risks and recognize research institutions as strategic partners rather than auxiliary providers.

A recurring theme throughout Biocam's evolution is the difficulty researchers face in transitioning from R&D to business-oriented development. While scientific expertise is essential in early TRL stages, later phases demand entrepreneurial and managerial competencies to navigate commercialization challenges [44]. This disconnect between research and business execution is not just a matter of individual skill gaps but an institutional challenge, where research culture often prioritizes knowledge creation over commercial viability and scalability.

The government and support entities played a crucial role in Biocam's evolution by facilitating funding, legal protection, and regulatory compliance. However, their approach remained largely project-based, with limited follow-up on long-term commercialization impacts. This suggests a missed opportunity to establish systemic policy frameworks that bridge the gap between research and industry adoption [45]. A key insight from this study is that governments should not only fund R&D but also foster long-term industry adoption mechanisms. This could include:

- Incentives for early-stage industrial investment in sustainable technologies
- Regulatory frameworks that facilitate market entry for eco-friendly innovations
- Support programs for SMEs to integrate sustainable solutions into their supply chains.
- Mechanisms to ensure that publicly funded research leads to commercially viable applications.

The limited impact of government agencies in securing industrial buy-in for Biocam suggests that public policy should evolve from a funding-centric model to an ecosystem-building approach, ensuring that sustainable aquaculture innovations do not remain isolated research outputs but become industry-wide solutions.

This study contributes valuable insights into how sustainable technologies can be developed, tested, and commercialized in aquaculture and similar industries. The integration of TRL theory, stakeholder theory, and sustainability principles illustrates that innovation is not solely a technological challenge but a multi-dimensional process requiring social, economic, and regulatory alignment [10], [15], [33]. This case suggests the following best practices for future sustainable technology initiatives:

- Early engagement with industrial stakeholders to align expectations and ensure market readiness.
- Diversified funding strategies that combine public funding with private investment to reduce dependency on governmental cycles.
- Cross-disciplinary training for research teams to incorporate business, marketing, and regulatory skills.
- Stronger policy frameworks that ensure R&D investments translate into industry-wide adoption and market penetration.

Biocam's development is a sample of the broader challenges and opportunities within sustainable aquaculture innovation. The balance between technological validation, stakeholder alignment, and commercialization demonstrates that successful sustainability-driven innovation requires an ecosystem perspective. As sustainability continues to be a global priority, future research and policy should focus on creating adaptive innovation ecosystems that can support long-term commercialization, multi-stakeholder collaboration, and financial resilience. The case of Nutriaqua serves as a valuable blueprint for achieving these goals, not just in aquaculture but across various sectors working towards environmental and economic sustainability.

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