

**Aquaculture vs decarbonization through
industrial symbiosis:
The role of bivalve shell recycling**

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Abstract

Recycling mussel shells offers environmental and industrial benefits. As a by-product of aquaculture and food processing, shells are often discarded, contributing to waste management challenges and costs. Recent studies highlight their potential as a sustainable source of high-purity calcium carbonate (CaCO₃), which can be extracted through processes involving washing, grinding, and calcination. This valorization reduces waste volumes, lowers disposal expenses for producers and introduces low-cost raw material to the CaCO₃ market. Notably, calcium derived from mussel shells can be utilized in emerging technologies such as calcium looping (CaL) for CO₂ capture, where calcium oxide (CaO) acts as a regenerable sorbent. Using shell-derived calcium in such applications supports circular economy principles and enhances the environmental performance of carbon capture. The MATSHELL project explores the potential of recycling bivalve shells to produce biogenic CaCO₃ and reuse for high-value applications. Findings show that biologically sourced precipitated CaCO₃ offers a competitive alternative to conventional sources, with rising market demand in high-value sectors. However, key barriers exist, including supply chain integration, regulatory complexity, and limited industrial adoption. The results of our analysis, conducted by interviewing a panel of experts, identified potential actions to address the challenges in accordance with industrial symbiosis models. The potential of the developed model was enhanced by integrating appropriate activities to optimize its implementation.

Keywords: aquaculture, waste reduction, circular economy, calcium carbonate.

JEL classification: Q22, Q00, Q5, Q53, Q57

First submission: 30th September 2025, accepted 30th January 2026

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1. Introduction

In recent decades, the aquaculture industry has experienced significant growth across different regions, driven by the growing interest in healthier products and more health-conscious dietary patterns (FAO, 2024). However, production within the European Union has stagnated, despite political support, investments, and research efforts (FAO, 2024; Guillen et al., 2025). Historically, several EU countries were leaders in aquaculture, particularly in the production of low trophic level species such as mussels and oysters. However, the mussel industry has faced environmental constraints, economic challenges, and regulatory complexities that have impeded its growth (Avdelas et al., 2021).

The EU's mussel production, which peaked in the late 1990s at over 600,000 tons, declined by 20% by 2016 (FAO, 2024). This reduction represents a significant portion of the stagnation in EU aquaculture. Several factors contribute to this decline, including climate change, harmful algal blooms, increased sea temperatures, ocean acidification, and extreme weather events. These environmental stressors impact mussel growth rates, reproduction cycles, and overall productivity. Additionally, the presence of pollutants such as heavy metals and microplastics in coastal waters raises concerns about food safety and marketability (Quintáns-Fondo et al., 2016).

Also, the entry of cheaper and increasingly dominant importers into the EU market (Garlock et al., 2020) has undermined the profitability of domestic producers, many of whom operate small-scale family businesses with limited economies of scale due to the fragmentation of producers, a lack of coordinated marketing strategies, and difficulties in obtaining new licenses for expansion (Soliño & Figueras, 2025). Focusing on the production side, a promising approach to revitalize the molluscs sector lies in the adoption of industrial symbiosis, where different industries collaborate to create mutually beneficial exchanges of resources, waste, and by-products with the idea of creating profitable circular economy models (Masi et al., 2025; Zhan et al., 2022; Jović et al., 2019; Silva et al., 2019).

Traditionally considered as waste, the shells of molluscs are often discarded during aquaculture and food processing, generating significant disposal costs and environmental burdens for producers. However, recent research has revealed that mussel shells contain up to 95% calcium carbonate (CaCO_3) (Azarian & Sutapun, 2022), a valuable material with wide-ranging industrial applications (Hamester et al., 2012).

Several practical experiences across Europe have demonstrated both the potential and the limitations of reusing bivalve shells as secondary raw materials (e.g. Barros et al., 2009). In the Algarve region of Portugal, surveys among shellfish producers revealed that around 67% of bivalve shells are still disposed of as common waste, while only a limited share is dried, crushed, and reused (Magalhães et al., 2024). The main challenges identified include the absence of standardized collection systems, insufficient logistical infrastructure, and a lack of awareness regarding the economic and environmental value of these materials, despite consistent literature on the topic (e.g. Francis, 2025; Morris et al., 2016, 2019; Summa et al., 2022; Yao et al., 2014; Zhan et al., 2022). The shells are often mixed with organic residues, increasing the costs of storage, transportation, and treatment (Medina Uzcátegui et al., 2022). Furthermore, the regulatory framework does not clearly classify shells as by-products, which discourages industries from investing in reuse strategies (Magalhães et al., 2024).

An emerging case of circular valorisation is represented by Wast3D Shells¹, created in 2024 in Taranto (Italy), which focuses on sustainable materials for building and infrastructure industry². While it is too early to evaluate the long term viability of the initiative, this example shows that when technical innovation is combined with local resource management, shell recycling can create new value chains and reduce dependence on virgin mineral extraction, and it validates former scientific suggestions (e.g. Fu et al., 2022; Her et al., 2021). A review of other applications of shell derived CaCO₃ can be found in Hart (2020). Beyond the immediate economic and environmental benefits, the calcium extracted from mussel shells holds potential for integration into advanced technologies, particularly in the field of carbon capture (Namikawa & Suzuki, 2024). In processes such as calcium looping (CaL), calcium oxide (CaO) derived from shell calcination serves as a regenerable sorbent for CO₂ removal (De Lena et al., 2022).

Nevertheless, the scalability of these processes is constrained by the heterogeneity of shell composition (Schioapu et al., 2025), contamination from marine biofilms, and the energy intensity of calcination (He et al., 2023). Moreover, the absence of cooperative networks linking aquaculture, waste management, and manufacturing sectors represents a structural barrier to the large-scale adoption of shell-derived materials. So, these initiatives remain isolated and highly dependent on regional support, lacking integration with broader industrial ecosystems.

Despite these obstacles, the valorisation of bivalve shells offers a compelling opportunity to align business and industrial strategies with fundamental circular economy principles (Zorpas, 2024; Uvarova et al., 2023; Veleva & Bodkin, 2018), as well as with carbon mitigation imperatives. The transformation of shells into calcium carbonate could serve dual purposes: reducing the environmental burden of shell waste and providing a renewable source of carbon capture material for industries with high CO₂ emissions, such as cement, lime, and steel production. Integrating this process within an industrial symbiosis framework could create localized loops where shell waste from coastal areas is redirected toward nearby emission-intensive industries.

Industrial symbiosis (IS) is commonly acknowledged as a sub-field of Industrial Ecology, and it represents a collaborative approach where traditionally separate industries engage in the physical exchange of materials, energy, water, and by-products, in order to achieve competitive advantage and reduce environmental impact (Chertow, 2000; Lombardi & Laybourn, 2012). IS processes are designed to enhance sustainability and economic performance by reducing costs, minimizing waste, and optimizing resource use. Consequently, IS strategies are considered from some scholars as expression of circular economy oriented business behaviour (Uvarova et al., 2023; Zorpas, 2024). As highlighted by Scafà et al. (2018), three main models of IS are identified by literature. First model recovers the principles of industrial districts, its paradigm being the pioneering and long lasting experience of Kalundborg Symbiosis (Cheshmehzangi, 2025; Ehrenfeld & Gertler, 1997). A second model is the Eco-Industrial Parks. The main difference in respect of districts, is that former mainly emerge from bottom-up processes and cooperative behaviours among agents

¹ <https://wast3dshells.com/>.

² <https://circulareconomyforfood.eu/en/wast3d-shells-circular-innovation-from-mussels-to-concrete>.

(Aviso et al., 2022) which are linked by a symbiotic supply chain (Brandao et al., 2025), while the latter are the outcome of a conscient, top-down, deliberate strategy (Mintzberg & Waters, 1985). Third model aligns with the idea of designing networks and providing platforms for enabling IS. National Industrial Symbiosis Programme (NISP) in the UK (Jensen et al., 2011) is a well-known example of tool provider, from the CRISP software to its successors (Yeo et al., 2019). These platforms leverage intelligent systems and algorithms (Zhao et al., 2025) to identify and recommend potential synergies for waste and resource reuse (Silva et al., 2022). However, IS platforms face significant challenges, linked to limited sustainability commitment, poor cooperation, and technical as well as economic barriers (Krom et al., 2022). Challenges are confirmed across literature. For instance, review from Grant et al. (2010) found that nine of 17 ICT tools for IS reviewed in the paper were no more in use. In addition, focusing on past experiences in IS, scholars highlight the existence of various drivers and barriers that influence the pursuit of eco-sustainable economic development through the creation of symbiotic networks (Boom-Cárcamo & Peñabaena-Niebles, 2022). The study by Henriques et al. (2021) emphasizes that the impact of these factors varies across different industries, presenting a complex intervention landscape that requires tailored measures to effectively address sector-specific needs. Regulation, intermediation, spatial proximity, and economic returns appear to be the main incentives for companies to invest in symbiosis projects, while social, technological and economic aspects tend to be more significant obstacles to establishing exchange networks (Neves et al., 2019). Another relevant aspect is the lack of proximity between the two ends of the symbiotic chain (Chrysikopoulos et al., 2024). The presence of industrial areas capable of attracting multiple businesses and creating dense networks of relationships establishes reference hubs that can drive industrial symbiosis (Yadav & Majumdar, 2024).

Several studies, also, have identified critical bottlenecks in the implementation of industrial symbiosis, particularly during its final stages, where firms must rigorously evaluate the trade-offs between costs and benefits within competitive market environments (Boom-Cárcamo & Peñabaena-Niebles, 2022; Chrysikopoulos et al., 2024; Henriques et al., 2021; Neves et al., 2019; Sellitto et al., 2025). Enterprises often exhibit a reluctance to adopt innovative solutions when operating under frameworks that do not facilitate risk-sharing, thereby impeding the uptake of new technologies and processes (Diaz et al., 2024; Henriques et al., 2022; Ventura et al., 2025). This cautious approach can significantly constrain the full utilization of research outputs and delay the integration of scientific advancements into industrial symbiosis systems.

Building on these experiences, the following research question emerges:

Can the recycling of bivalve shell waste, when integrated into industrial symbiosis networks, provide a sustainable pathway for calcium carbonate production that enhances CO₂ capture in high-emission sectors?

In this context, the recently launched “Development of Advanced Materials for Industry and Cosmetics Derived from Waste Bivalve Shells from Fishing and Aquaculture” (MATSELL) project has brought together multiple research institutions and production facilities in Italy to experiment the latest advancements in processing and extraction techniques aimed at obtaining valuable products and raw materials

from mussel shells. Specifically, it aimed to repurpose waste bivalve shells from aquaculture to develop advanced materials for high value industries. As a model of the circular economy, MATSHELL demonstrated the ecological, economic, and social benefits of utilizing shells, which contributed to biodiversity conservation, economic gains for farmers, and sustainability in human activities. The project expanded the potential applications of calcium carbonate, ensuring its environmental and commercial viability.

In the following, we highlight the perspectives in terms of industrial symbiosis that reflect the activities and research findings conducted in the field within the framework of MATSHELL project, supported by a SWOT analysis that provided insights into strengths, weaknesses, opportunities, and threats of the proposed symbiotic approach.

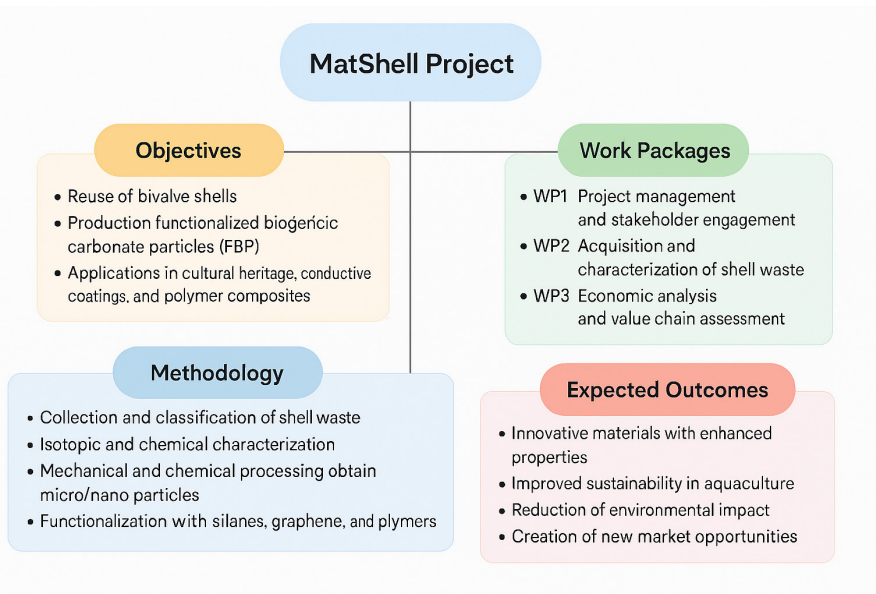
2. MATSHELL project overview and proposition

MATSHELL project aimed to repurpose discarded shells resulting from farmed mollusc production. Given the high level of innovation in the processes involved, the project also sought to develop and experimentally scale up ground particles of biogenic calcium carbonate. MATSHELL exemplified circular economy principles, particularly because shells are a valuable biomaterial. The initiative not only enhanced the sustainability of the aquaculture sector but also provided several benefits, including ecological advantages by contributing to biodiversity conservation and ecosystem functionality, secondary economic gains for mollusc farmers and processors, and social benefits linked to human well-being through the increased sustainability of anthropogenic activities involved in transformation processes. The scientific and technological advancements developed within MATSHELL enabled the production of fine biogenic particles (FBP) with customized functional groups, expanding its potential applications beyond conventional uses of calcium carbonate.

The project was designed considering the unique compositional, structural, and mechanical properties of shells as well as their widespread availability. These composite materials consisted of calcium carbonate and a small fraction (2-5% by weight) of an organic bio-macromolecular matrix, which provided the shells with mechanical properties that could not be synthetically replicated in laboratory settings.

The methodology involved collecting and classifying shell waste, performing isotopic and chemical characterization, and processing shells into micro- and nano-sized particles through mechanical and chemical techniques. The project was structured into three work packages: project management and stakeholder engagement, acquisition and characterization of shell waste, and economic analysis with value chain assessment. Expected outcomes included innovative materials with superior mechanical and chemical properties, improved sustainability in aquaculture, reduced environmental impact, and the creation of new market opportunities within a circular economy framework. In Figure 1 we report a detailed infographic summarizing the MatShell Project, with color-coded sections for Objectives, Methodology, Work Packages, and Expected Outcomes.

Figure 1 – Detailed infographic summarizing the MatShell Project, with color-coded sections for Objectives, Methodology, Work Packages, and Expected Outcomes



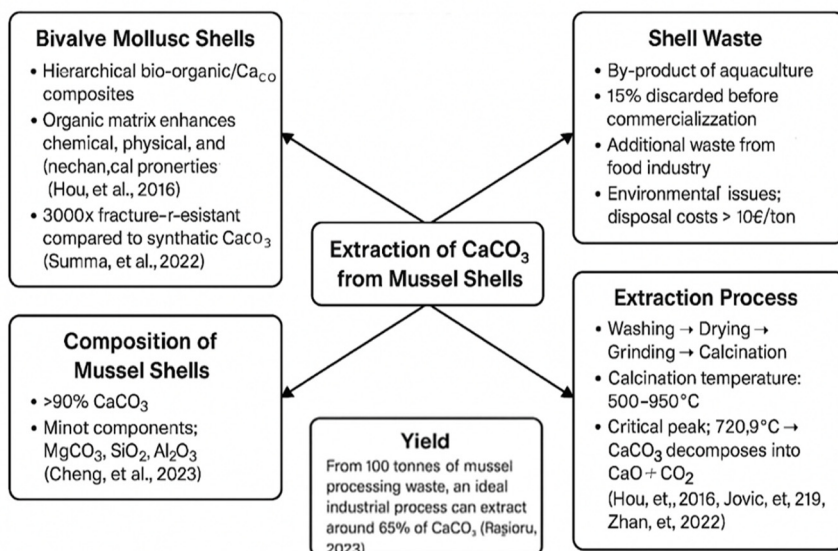
a. MATSHELL’s scientific foundations: Literature Review of Bivalve Shell Waste Recycling Techniques

As attested by consolidated literature, bivalve mollusc shells are sophisticated hierarchical composites composed of calcium carbonate and organic materials, exhibiting remarkable advanced functional properties through their intricate nano-structural design (Hamester et al., 2012; Taylor & Layman, 1972). Their unique structure arises from the incorporation of a small organic matrix within the calcium carbonate crystal lattice (Hou et al., 2016). Although this organic matrix constitutes only 2-5% by weight, it significantly enhances the chemical, physical, optical, and mechanical properties of the material, making it 3000 times more fracture-resistant than synthetic or geogenic CaCO₃ (Summa et al., 2022).

These shells are by-products of bivalve mollusc aquaculture. A case study from Central Java production estimates that green mussel shells accounts for 70% of the total production (Ismail et al., 2022) which, given a world mussel production of around 2 million metric tons (Gosling, 2021), equals to around 1.35 million metric tons of CaCO₃ stored in mussel shell yearly. Data from MATSHELL reveals that approximately 15% of the molluscs’ weight is discarded as unwanted waste before commercialization (e.g., for mortality), not accounting for the additional source of shell waste originated from food processing industries and consumption. Most of this waste is either sent to landfills or dumped into the sea, causing several environmental issues (Magalhães et al., 2024). This part of the processing chain is unsustainable, and disposal costs may be significant, according to applicable regulation framework.

As highlighted in Figure 2, the extraction of calcium carbonate CaCO_3 from mussel shells follows a well-established process that involves washing, drying, grinding and calcination. The calcination of the shells is essential to obtain CaO , which is used in numerous industrial applications (Hou et al., 2016; Jović et al., 2019; Zhan et al., 2022). Mussel shells are mainly composed of CaCO_3 , and small amounts of other minerals such as MgCO_3 , SiO_2 and Al_2O_3 (Cheng et al., 2023). According to a general consensus in the literature relating experimental data from different geographic areas, from 100 tonnes of mussel processing waste, an ideal industrial process can extract around 65% of CaCO_3 (e.g., Alonso et al., 2021; Ismail et al., 2022; Roşioru, 2023). Pioneering industrial experience which started in 2003 in Galicia (Spain), showed both low level of efficiency and emissions problems. However, the learning curve was rapid, despite a plant oversized in respect of actual waste supply (Barros et al., 2009).

Figure 2 – Calcium carbonate (CaCO_3) extraction from mussel shell



Source: Author's own elaboration

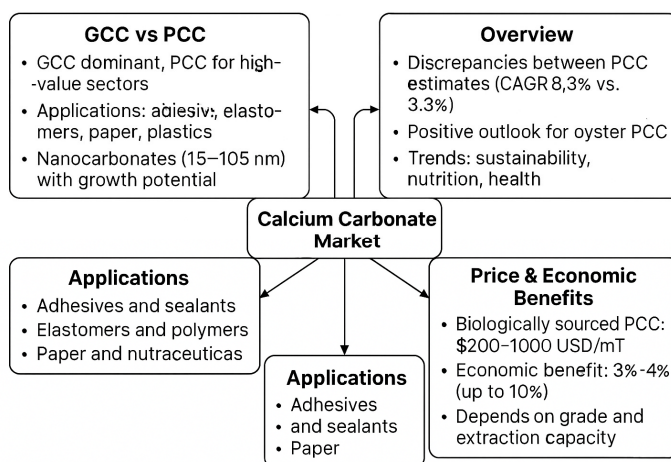
A recent study focusing on proxy products, tried estimating the economic and environmental viability of the industrialized process, concluding for an expected Internal Return Ratio of 12.7% and a yield in CaCO_3 of around 83% in respect of waste treated (He et al., 2023). The expected return is aligned with the market of investments in chemical industry, according to McKinsey sources (Lorbeer & Ezekoye, 2024).

b. Industrial Symbiosis Perspectives

Within the scope of MATSHELL, the waste primarily consists of mussels that, during the growth and finishing process, are deemed unsuitable for consumption and commercialization, such as specimens affected by mortality. This type of waste typically represents a significant proportion relative to the volume effectively marketed and imposes a specific disposal cost on producers' financial accounts. According to empirical data collected by MATSHELL, the incidence of waste in volume rises up to around 16% of production. Consequently, it is worthwhile to explore the potential for recycling this waste to obtain valuable raw materials for downstream production processes, in an IS perspective. Indeed, while acknowledging the growing debate about the under-conceptualization of circular economy (e.g. Nosková, 2025; Hirsch & Levin, 1999), we agree with industrial ecologists (e.g., Stahel, 2016; Blomsma & Brennan, 2017; Kirchherr et al., 2025) upon the strict linkage between IS and circularity. From our standpoint, Industrial Ecology can be considered as a precursor of circular economy frameworks, and Industrial Symbiosis represents the organizational effort provided by industries in order to achieve circular and sustainable goals (Corsini et al., 2024; Ramírez-Rodríguez et al., 2024; Veleva & Bodkin, 2018) while improving value production (Stahel, 2016).

For evaluating the potential for value creation, MATSHELL team integrated the scientific literature with research on CaCO₃ market available information. Converging sources from various commodity market analysts (ChemAnalyst, Fact, ...) indicate that the calcium carbonate market is expected to grow significantly in the coming years, both in the segment derived from rock fragmentation (Ground or GCC) and in the segment obtained through alternative extraction and synthesis processes (Precipitated or PCC) (See Figure 3 for a summary). Specifically, while GCC has been and will continue to be the dominant market component, PCC is of particular interest to high-value-added sectors, including adhesives, sealants, elastomeric materials, plastics, printing paper, nutraceutical products, and more. This is consistent with information available in the scientific literature (e.g. Francis, 2025; Summa et al., 2022; Zhan et al., 2022; Morris et al., 2016, 2019; Yao et al., 2014). In addition, PCC-generating processes appear to be capable of producing, at least in part, ultra-fine particles (15-105 nm, known as "nanocarbonate"), which have strong growth potential (Barros et al., 2009; Ismail et al., 2022). These nanoparticles can (or they could in the future) serve as specialized antibacterial agents, components of anticancer drugs, and dietary supplements (Cai et al., 2025), as well as being used in the more traditional construction sector, a major consumer of bulk materials (see Fu et al., 2022).

Figure 3 – Calcium Carbonate market overview



Source: Future Market Insight, Straits Research, Coherent Market Insights, IMARC Group PW Consulting

To the best of our knowledge, no specific market data on mussel-derived PCC are available, but related information exists for PCC obtained from oyster shell processing. This market niche is driven by demand from high-value-added industrial sectors (dietary supplements, pharmaceutical products, personal care, animal nutrition), and, according to various analysts, it benefits from favourable regulatory developments as well as increased consumer environmental awareness.

Based on available data, the price of biologically sourced PCC varies significantly, according to the regional market³ (North America, Europe, APAC) and CaCO₃ grade. He et al. (2023), estimated relevant prices for biological sourced PCC ranging between 200 and 1000 USD/mT, referring to bulk prices found on Alibaba.com. Our researches on commercial sites (IndiaMart, MadeInChina) yield similar results. After combining all the context elements with empirical data, we consider that extracting and selling biologically sourced PCC might provide mussel producers a gross economic benefit between 3% and 4% of production value, which is a conservative estimation. If we introduce more optimistic price estimations, the gross benefit could be estimated at 10% or more, according to the capacity of the extraction process to maximize high-end products, in line with He et al. (2023) estimations.

³ Source: chemanalyst.com

c. From Shell Waste to CO₂ Capture: The Potential of Calcium Looping

Aside from standard economic considerations about the market-value of shell derived CaCO₃, the recycling of mussel shells offers an interesting opportunity to support carbon capture technologies, particularly through the calcium looping process (Alonso et al., 2021). Calcium looping (CaL), also referred to as the regenerative calcium cycle (RCC), is a second-generation carbon capture technology that has gained significant attention for its potential to mitigate CO₂ emissions from industrial sources such as cement plants, power stations, and waste-to-energy facilities. The process is based on two reversible chemical reactions: carbonation and calcination, which enable the cyclic capture and release of CO₂ using CaO as a solid sorbent (Hanak et al., 2015).

In particular, CaL is a thermochemical process that captures CO₂ from flue gases using calcium oxide (CaO)-based sorbents, which react with CO₂ to form CaCO₃. The sorbents are regenerated through calcination, releasing concentrated CO₂ for sequestration or utilization, and restoring CaO for reuse. This closed-loop system offers multiple environmental and economic benefits.

One of the key advantages of CaL is its compatibility with high-temperature industrial processes, allowing for integration without significant infrastructure modifications. Unlike liquid absorbents used in amine scrubbing, CaL avoids issues such as corrosion and solvent degradation, offering a more robust and scalable solution for CO₂ capture.

Pilot-scale implementations of CaL have demonstrated promising results. A notable example is the TRL7 CFB-CaL pilot at La Pereda (Arias et al., 2024), which achieved CO₂ capture efficiencies exceeding 99% using circulating fluidized bed technology and biomass-fired calcination. The system was able to treat over 2000 Nm³/h of flue gases, showcasing the scalability and retrofitting potential of CaL in existing industrial setups. According to recent studies, calcined mollusc shells often display enhanced carbonation reactivity compared to natural limestone. This improved performance is linked to the residual porosity of shell-derived CaO, which facilitates gas diffusion and accelerates the chemical reactions (Hart & Onyeaka, 2020). By substituting conventional mineral resources with shell waste, the environmental impact of quarrying is also reduced, adding further benefits in terms of the circular economy and sustainability. Thus, shell recycling represents a promising pathway in decarbonization strategies (Adjei et al., 2025), and CaL process adds value to the waste treated (Anthony, 2011).

d. Proposal for an industrial symbiosis model

MATSHELL project has provided significant evidence that new extraction and processing techniques can yield high-purity calcium carbonate products from bivalve shell waste, confirming previous studies about the feasibility of transforming this biological residue into a valuable industrial resource (Francis, 2025; Schiopu et al., 2025; Cheng et al., 2023; Ismail et al., 2022; Zhan et al., 2022; Summa et al., 2022; Morris et al., 2019). Through an integrated experimental approach combining material characterization, process optimization, and environmental assessment, the

research has demonstrated that controlled calcination and precipitation routes can produce calcium carbonate of exceptional purity and crystalline stability. These characteristics make the resulting material suitable for a wide range of applications, spanning from pharmaceutical and nutraceutical formulations to advanced industrial processes such as calcium looping for CO₂ capture and reuse (Adjei et al., 2025; Alonso et al., 2021; Hart & Onyeaka, 2020; Hanak et al., 2015; Anthony, 2011).

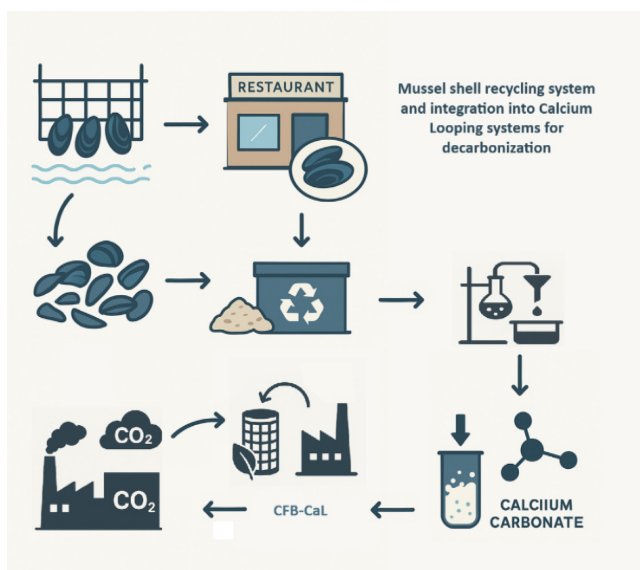
One of the central findings of the project concerns the intraspecies variability of outcomes based on both geographical and operational parameters, aside interspecies considerations (Piras et al., 2024). The mineral composition and microstructure of the shells were found to depend strongly on the local marine environment, aquaculture practices, and seasonal factors influencing shell growth. Such geographical differentiation affects the reactivity, whiteness index, and particle morphology of the extracted carbonates. In addition, MATSHELL team identified that the degree of pre-treatment, as cleaning, classification, and granulometric control of the shell waste, plays a decisive role in determining the final product quality. When the discarded shells are adequately sorted, washed, and mechanically refined prior to calcination, the extracted calcium carbonate exhibits superior physicochemical properties and higher market value. As illustrated in previous pages, these results confirm that the proper management of shell residues can lead not only to waste reduction but also to the creation of high-value materials.

However, some caveats apply. To the best of our knowledge, the first structured trial to industrialize CaCO₃ extraction from mussel shells was the Calizas Marinas experience (Barros et al., 2009). Calizas was a Galician company that actively operated in this market from 1999 to 2010 and, despite some achievements, it officially ceased its administrative existence in 2017. This happened despite a strong capitalisation (over €5 million in share capital), the involvement of many regional producers of mussels (43 companies), and the active support of the Autonomous Community of Galicia as a facilitator⁴. From our standpoint, two reasons clearly emerge for their failure: an extraction process that was not sufficiently mature, and the oversizing of the plant. This second point is crucial from the Industrial Symbiosis perspective, because it highlights deficiencies in the design and in the governance system, as mussel producers did not fully comply their engagement about waste drop-off. Following Chrysikopoulos et al. (2024), we can detect a vicious circle between scarce short term economic viability and the commitment of the network. In these conditions, the availability of financial means was not a sufficient anticipator of future returns, so it did not play the role acknowledged in the literature (e.g. Corsini et al., 2024). In addition, other biogenic CaCO₃ extraction research projects, highlight relevant challenges, in particular for oyster sourced biomaterial, as: high initial investment, competition with similar replacement products in the market, cost of research on high-quality product development, a thorough comparison of market product prices and production costs, a year-round supply of oyster shell processing waste, and maintaining the processing plant to guarantee a steady performance (Chowdhury & Ehimen, 2022). Finally, as reminded in introduction, the experience of Wast3d Shell in Taranto is still too new to be scrutinized.

⁴ Source: www.interfishmarket.com.

These experiences alert about some criticalities. First, the existence of a valuable disposal is not sufficient for sustain industrial symbiosis. Second, the existence of a clear demand for disposal derived products is not sufficient for sustain industrial symbiosis. Third, the existence of incentives is not sufficient for sustain industrial symbiosis. As supported by broad literature, Industrial Symbiosis requires a well-established ecosystem (Morales & Diemer, 2019) marked by shared values, cooperation, and coordination (Marian R. Chertow & Ehrenfeld, 2012), where appropriated metrics allow for full account of net benefits (Mirata et al., 2024; de Araujo et al., 2011).

Figure 4 – Mussel shell recycling system



Source: Author's own elaboration

In response to these insights, MATSHELL project developed a proposal for an industrial symbiosis model that integrates shell waste valorisation with carbon-intensive sectors. The model leverage on the optimal plant sizing by He et al. (2023), which is around 1/8 of Calizas' size, on high TRL in specific pilot plant (Arias et al., 2024), and on high performances of biogenic CaCO_3 for CaL (Adjei et al., 2025; Arias et al., 2024). This niche design avoids most of the criticalities raised by Chowdhury and Ehimen (2022). The small sizing of the projected plant allows for localized networks (Chertow, 2000) where shell residues are collected from coastal regions, processed into refined calcium carbonate, and supplied to industries involved in cement, lime, or steel production, sectors with substantial CO_2 emissions and high demand for carbonate materials. This reduces the need for complex symbiotic upstream networks, allowing for simpler models based on the design of diffused eco-parks (Scafà et al., 2018). Downstream networks will complement the monitoring for outlet markets and revenue securing.

The overall system architecture and process integration developed within MATSHELL are summarized in Figure 4, which schematically represents the proposed industrial symbiosis pathway from shell collection to calcium carbonate production and its downstream applications. The proposed system begins with the collection of mussel shells from seafood processing facilities and foodservice establishments. These shells undergo pre-treatment processes including washing, drying, and grinding, followed by chemical purification to isolate CaCO₃. The extracted calcium carbonate is then utilized in the production of solid sorbents for calcium looping systems (Hanak et al., 2015).

This configuration aligns theoretical perspectives on industrial ecology with practical applications of circular economy as discussed before, aiming to close both material and carbon loops through regional cooperation and resource optimization.

To assess the feasibility and strategic positioning of the proposed integrated system, the research team adopted a qualitative methodology based on semi-structured interviews with scientific experts and sector stakeholders. This approach involved presenting the developed industrial symbiosis model, eliciting expert perceptions, and systematically identifying the factors they considered as supporting or opposing its implementation. The results of the analysis are presented below in a SWOT analysis format.

3. Data and method

The empirical component of this research was conducted on a purposive sample composed of thirteen university-based researchers and six stakeholders from the production sector, reflecting the interdisciplinary and multi-actor approach adopted within the MATSHELL project. The academic sample included ten chemists and three marine ecologists, each contributing specific expertise related to the characterization and environmental assessment of bivalve shell waste. The group of chemists was primarily responsible for the classification and compositional analysis of mussel shells, focusing on variations in their physical and chemical properties as a function of geographical origin and the production chain from which the waste was derived. Their activities encompassed both the laboratory-based examination of mineral content, crystalline structure, and impurity profiles, and the comparative assessment of samples collected from different coastal and aquaculture sites. The aim was to identify how local environmental conditions, water chemistry, and processing practices influence the quality and potential recyclability of shell residues. In parallel, the three marine ecologists within the research team investigated the biological and environmental aspects of the production sites, with particular attention to the ecological footprint associated with shellfish cultivation and shell waste management. Their work involved evaluating the potential impacts of shell disposal on benthic ecosystems, assessing nutrient cycling, and identifying opportunities for mitigation and restoration. This ecological perspective complemented the chemical and material analysis by situating shell recycling within a broader environmental sustainability framework. To extend the analytical perspective beyond the academic domain, the sample was expanded to include six participants representing the entrepreneurial and organizational dimensions of the sector. These comprised four shellfish producers directly

involved in the MATSHELL project and two representatives from the Italian Association of Shellfish Producers. Their inclusion allowed for the exploration of the practical feasibility, economic constraints, and institutional attitudes toward shell recycling and industrial symbiosis models.

The following table summarizes the panel of experts from the MATSHELL project used in this study:

Table 1 – Different categories of experts involved in MATSHELL project, their characterization and main tasks

Expert Characterization	Expert Type	Main Tasks in the Project
Chemist	<ul style="list-style-type: none"> • Academic • 10 experts 	<ul style="list-style-type: none"> • Classification and compositional analysis of mussel shells • Study of physical and chemical properties based on geographical origin and production chain • Laboratory analysis of mineral content, crystalline structure, and impurity profiles • Comparative assessment of samples from coastal and aquaculture sites
Marine Ecologist	<ul style="list-style-type: none"> • Academic • 3 experts 	<ul style="list-style-type: none"> • Analysis of biological and environmental aspects of production sites • Assessment of the impact of shell disposal on benthic ecosystems • Study of nutrient cycling and identification of mitigation and restoration opportunities • Integration of ecological perspective into the environmental sustainability framework
Mussel Producer	<ul style="list-style-type: none"> • Private • 4 experts 	<ul style="list-style-type: none"> • Providing operational data and waste management practice • Evaluation of technical feasibility of shell recycling • Contribution to defining economic and practical constraints
Representative of the Italian Association of Shellfish Producers	<ul style="list-style-type: none"> • Private • 2 experts 	<ul style="list-style-type: none"> • Analysis of institutional and regulatory dynamics • Support for promoting industrial symbiosis models • Discussion of economic and organizational implications

All participants were presented with the proposed industrial symbiosis framework (see Figure 4). Feedback was collected using a SWOT analytical framework, assessing strengths, weaknesses, opportunities, and threats, in order to capture both disciplinary insights.

4. SWOT analytical framework

The SWOT analysis framework has its roots in 1950s, with the seminal works of Stewart about strategy and long-range planning (Puyt et al., 2020) Several practi-

tioners and scholars contributed to its development (Helms & Nixon, 2010; Palazzo, 2024), and today it is acknowledged as a foundational methodology for strategic planning across diverse organizational contexts (Freyn & Hoffman, 2023), despite some issues (King et al., 2023). Its analytical strength lies in its ability to distinguish between internal factors, which fall within an organization’s control, and external factors, which are influenced by broader environmental dynamics (Benzaghta et al., 2021). Strengths and weaknesses denote internal attributes that respectively facilitate or hinder the achievement of organizational objectives, whereas opportunities and threats represent external conditions that either support or challenge strategic goals. Although methodologically simple, SWOT’s analytical potential has been substantially enhanced through its integration with complementary models and decision-making tools (Yavuz & Baycan, 2013). Its adaptability has allowed it to be embedded within broader strategic frameworks, thereby expanding its analytical scope.

Figure 5 – SWOT Template used in this study.

SWOT ANALYSIS TEMPLATE	
STRENGTHS	WEAKNESSES
OPPORTUNITIES	THREATS

In applied settings, SWOT is commonly operationalized through matrices that guide the formulation of strategic alternatives (see Figure 5), namely: SO (strengths–opportunities), ST (strengths–threats), WO (weaknesses–opportunities), and WT (weaknesses–threats).

In our study, we strengthened the analytical robustness of the SWOT framework by incorporating expert opinions from the various research units involved in MATSHELL project, as well as insights from private stakeholders as showed in Table 1. As suggested in literature (Helms & Nixon, 2010; Yavuz & Baycan, 2013; Bull et al., 2016), by systematically incorporating expert assessments and stakeholder contributions, this framework generates multidimensional perspectives and enables the quantification of qualitative SWOT factors, thereby strengthening the reliability and precision of strategic evaluations.

5. Results and discussion

The analysis of expert interviews provided a rich set of insights that proved fundamental for advancing the study's analytical framework. The initial phase involved gathering qualitative data and perceptions from a diverse group of stakeholders, each offering nuanced perspectives on the dynamics, challenges, and opportunities characterizing the symbiotic system under investigation. This exploratory stage was essential not only for identifying recurring themes but also for capturing the heterogeneity of viewpoints that typically emerges when consulting experts with varied backgrounds and professional experiences.

Following this first round of data collection, a systematic reclassification process was undertaken to organize the information within the structure of a cumulative SWOT analysis. The raw insights derived from the interviews were reorganized and mapped onto the four quadrants of the SWOT framework. This step allowed for the transformation of individual observations into more coherent and analytically meaningful categories. The reclassification aimed to identify emerging patterns, reduce redundancy, and group related factors in a way that facilitated the recognition of broader macro-areas of strategic relevance.

Once these macro-areas were delineated, an additional effort was made to anchor each thematic cluster in the existing academic literature. This step served a dual purpose: it validated the empirical findings emerging from the expert interviews, and it reinforced the analytical robustness of the SWOT categorization through established theoretical references. For each macro-area, a relevant theoretical framework or scholarly contribution was identified to substantiate the interpretation of the qualitative evidence. This alignment ensured that the empirical insights were not only grounded in expert experience but also situated within a broader conceptual and methodological context. The integrated results of this process are presented below, offering a comprehensive overview of how interview-based insights were translated into structured analytical categories supported by theoretical foundations. The synthesis illuminates the main strategic orientations that emerged for each quadrant and provides a clear depiction.

Subsequently, a holistic verification of the overall strategic model was conducted. This phase entailed revisiting the SWOT-derived macro-areas and examining their interconnections to ensure internal consistency and strategic coherence. In doing so, specific actions were formulated in relation to each area of the SWOT analysis. These actions were designed to leverage strengths, mitigate weaknesses, seize opportunities, and address threats through targeted interventions. The resulting strategic proposals offer actionable guidelines that can inform decision-making processes and support long-term planning efforts.

6. SWOT Analysis Results

Strengths

- **Technological Maturity:** Calcium looping has reached a Technology Readiness Level (TRL) above 7, indicating that the process has been demonstrated in operational environments and is ready for industrial deployment (Arias et al., 2024).

The maturity of CaL systems ensures that integration with existing industrial infrastructure is technically feasible and economically viable. Furthermore, the chemical extraction of CaCO₃ from mussel shells is based on well-established purification protocols, allowing for consistent quality and scalability (Schiopu et al., 2025; Magalhães et al., 2024; He et al., 2023; Ismail et al., 2022; Hou et al., 2016; Barros et al., 2009). Building on this foundation, MATSHELL project has played a pivotal role in consolidating and systematizing the various extraction methodologies proposed in the scientific literature. Through extensive experimental validation, MATSHELL has codified a series of efficient protocols tailored to the specific characteristics of mussel shells, depending on their origin, whether from aquaculture, industrial processing, or post-consumption waste. This differentiation enables the selection of the most suitable process in each context, optimizing both yield and product quality while mitigating the impact of potential contaminants. As a result, the project has laid the groundwork for a flexible and adaptive processing framework. This advancement is particularly valuable for industrial implementation, where variability (Piras et al., 2024) in raw material composition can pose significant challenges to standardization and performance consistency in downstream carbon capture applications.

- **Process Compatibility:** The modular architecture of CaL systems enables flexible integration across a wide range of industrial emitters, including cement plants, steel mills, and power generation facilities (Adjei et al., 2025; De Lena et al., 2022; Hanak et al., 2015; Anthony, 2011). This diversity significantly enhances the potential for identifying suitable symbiotic partners for decarbonization initiatives. In particular, regions with established mussel farming operations can strategically align with nearby industrial emitters to optimize material flows and minimize logistical burdens. Beyond technical efficiency, such localized systems offer significant social and territorial benefits (Cheshmehzangi, 2025; Sellitto et al., 2025; de Araujo et al., 2011). By embedding decarbonization practices within existing regional structures, such as aquaculture, food processing, and industrial manufacturing, these initiatives can foster greater civic engagement and public appreciation for sustainable industrial transformation (Chertow, 2000). The visible reduction of waste and the creation of symbiotic relationships between sectors enhance the perceived value of these infrastructures. This is especially relevant in coastal urban areas, where industrial facilities often face growing public opposition due to environmental concerns. Integrating carbon capture with circular resource use, such as mussel shell recycling, can shift public perception, positioning these facilities as contributors to ecological regeneration rather than sources of degradation. As a result, strategic localization not only improves logistics but also strengthens the social license to operate in sensitive urban and coastal contexts (de Araujo et al., 2011).

Weaknesses

- **Complexity of Symbiotic Linkages:** Establishing a robust supply chain that connects seafood waste producers, chemical processors, and CO₂ capture facilities requires significant coordination to manage the interdependence of parts (Aviso et al., 2022). This interdependence is binding, especially for the part of the mussel farms that have difficulty imagining a second outlet market (that of

shells and production waste) in addition to the primary one familiar to them (the food products market). This double market challenge is difficult to manage also because of a clear imbalance of entrepreneurial skills towards their first and historical market, rather than in a completely different market with little or even totally unknown dynamics of competition and exchanges. The hesitation for the mussel farms stems also from the difficulty of integrating such a market internally, given the required technical expertise and the vastly different technologies compared to those used in their respective areas of operation (Summa et al., 2022). This hesitation manifests itself in a fear of establishing a relationship of interdependence between the parties, which is often seen as a threat and a constraint on the freedom of future choices of companies (Ventura et al., 2025). This paradoxically turns out to be more surmountable if one looks at it from the point of view of scientific collaborations with engineering systems that can facilitate the structuring of extraction production processes in an efficient manner, thanks to synergies with research centres and with the provision of high and specific technical skills (Aviso et al., 2022). In this case, the strong scientific collaboration that could be triggered following experimental pilot projects turns out to act as a driving force rather than as a barrier to action. Furthermore, the development of projects turns out to be an opportunity for the creation of those collaborative relationships that can take root and allow the positive evolution of an effective industrial symbiosis system.

- **Variability** in shell composition and contamination levels can introduce quality control challenges in the CaCO_3 extraction phase. Factors such as environmental exposure and residual organic matter can affect the purity and consistency of the extracted material. Contaminants like heavy metals, biofilms, and food residues may interfere with chemical purification steps, requiring additional processing stages that increase operational complexity and cost. Ensuring uniform quality of CaCO_3 is critical for its application in calcium looping systems, where sorbent performance depends on precise chemical properties (Arias et al., 2024; Anthony, 2011; De Lena et al., 2022). Therefore, robust quality control protocols and standardized input streams are essential for industrial scalability.
- **Capital Intensity**: While the core technologies involved, waste collection, chemical processing, and carbon capture, are mature, their integration into a cohesive industrial ecosystem demands substantial upfront investment (Chowdhury & Ehimen, 2022; He et al., 2023). To overcome financial barriers, especially in smaller municipalities or decentralized regions, a structured collaboration between public authorities and the banking sector is essential. Facilitating access to capital through green financing instruments or public-private partnerships can accelerate deployment. Moreover, investment can be framed as environmental remuneration (Anthony, 2011), where decarbonization outcomes are monetized and accounted for as carbon credits or avoided emissions, thus creating measurable value and incentivizing participation across institutional and financial stakeholders.

Opportunities

- **Expanding Decarbonization Market**: The global push for decarbonization, driven by regulatory frameworks such as the EU Green Deal and national carbon neutrality targets, is accelerating the adoption of CO_2 capture technologies. CaL

is gaining traction due to its cost-effectiveness and compatibility with high-temperature industrial processes. The demand for sustainable sorbents is expected to rise, creating a favorable market for bio-derived CaCO_3 (Summa et al., 2022). As for market prices of carbon carbonate, European prices have fluctuated between 300 USD/mT and 410 USD/mT since 2022. However, these prices are for the entire market regardless of source (GCC or PCC), and they are strongly influenced by the construction sector dynamics, which is not the main target for biologically sourced CC. Also, it is worth noticing that some supply chain disruptions happened, especially in the US during 2024⁵, which is one of the risks that make industrial symbiosis of strategic interest. With regard to the specific pricing of biologically sourced calcium carbonate, market analysis proved to be challenging due to its niche nature and the confidentiality maintained by most producers regarding price listings.

- **Policy Incentives and Circular Economy Mandates:** Governments are increasingly supporting circular economy initiatives through subsidies, tax incentives, and research funding. The integration of mussel shell recycling into carbon capture aligns with these policy trends, potentially unlocking financial and regulatory support. Moreover, the system contributes to multiple Sustainable Development Goals (SDGs), including responsible consumption, climate action, and industry innovation (Masi et al., 2025; Ramírez-Rodríguez et al., 2024; Summa et al., 2022). Financial instruments, including green bonds and innovation grants, may be leveraged to support infrastructure development and stakeholder coordination. Additionally, the system's alignment with SDGs enhances its appeal to public and private actors seeking to meet ESG (Environmental, Social, and Governance) targets (Francis, 2025; de Araujo et al., 2011).
- **Regional Development and Job Creation:** The establishment of localized processing hubs for shell waste and CaCO_3 production can stimulate regional economies, particularly in coastal areas with strong aquaculture sectors. This model promotes green job creation and supports the transition to low-carbon industrial ecosystems (Ventura et al., 2025). When strategically positioned near coastal industrial zones, these hubs can serve as catalysts for socio-economic revitalization. Many of these areas face progressive decline due to the environmental incompatibility of traditional manufacturing activities with current sustainability standards. By repurposing existing infrastructure and retraining local workforces, the development of mussel shell recycling and carbon capture facilities offers a pathway to industrial renewal. These hubs can absorb displaced labour from declining sectors, fostering inclusive employment and technological upskilling. Moreover, their proximity to both waste sources and emission-intensive industries enhances logistical efficiency and symbiotic integration (Jensen et al., 2011). This spatial strategy not only supports environmental goals but also reinforces regional resilience (Morales & Diemer, 2019) through sustainable industrial diversification.

⁵ Source: www.chemanalyst.com.

Threats

- **Geographical Dispersion of Symbiotic Nodes:** The effectiveness of the integrated system relies heavily on the spatial proximity between mussel shell waste sources, CaCO₃ processing facilities, and CO₂ capture sites (Cheshmehzangi, 2025; Morales & Diemer, 2019; Scafà et al., 2018). When these nodes are geographically dispersed, transportation costs and associated emissions can significantly reduce the environmental and economic benefits of the system. Logistical bottlenecks may also disrupt material flows, undermining operational reliability. Therefore, it becomes strategically essential to map and to identify coastal industrial zones and mussel production regions where these symbiotic-nodes naturally converge. Targeting such areas for the development of pilot systems can optimize logistics, reduce infrastructure costs, and accelerate deployment. These geographically concentrated and integrated hubs allow for streamlined material handling and foster industrial symbiosis by also implementing digital traceability systems (Zhao et al., 2025). This spatial planning approach enhances both the feasibility and sustainability of the mussel shell-to-carbon capture value chain.
- **Regulatory Uncertainty and Market Volatility:** While the decarbonization market is expanding, it remains sensitive to policy shifts and economic fluctuations. Changes in carbon pricing, environmental regulations, or public funding priorities could impact the viability of the system. For example, when regulations lack clear definitions and fail to introduce real disincentives for waste and pollution, companies perceive industrial symbiosis as excessively risky and refrain from committing resources (Chrysikopoulos et al., 2024). The absence of public financial support or easy access to funding, in fact, discourages symbiotic initiatives, given the high initial costs associated with infrastructure development, the adoption of new technologies, and research and development activities (Sellitto et al., 2025). The involvement of facilitators and public authorities in facilitating the exchange of industrial residues provides additional support by mitigating risk through research and development funding, tax incentives, and knowledge dissemination (Henriques et al., 2022; Ventura et al., 2025).

7. Proposed strategic actions for advancing mussel shell-based carbon capture initiatives

The proposed actions aim to operationalize an industrial symbiosis model that leverages mussel shell waste as a feedstock for calcium looping (CaL) processes, thereby contributing to carbon capture and circular economy objectives. These actions are structured across four dimensions: leveraging strengths, addressing weaknesses, capturing opportunities, and mitigating threats.

Actions leveraging strengths

The maturity of CaL technology (Arias et al., 2024) and the availability of validated extraction protocols provide a strong foundation for early implementation. To capitalize on these strengths, regional pilot hubs should be established in high-potential coastal zones where mussel farming and industrial CO₂ emissions are geographically concentrated. Such hubs would serve as integrated platforms for shell collection, pre-processing, and CaL operations, reducing logistical complexity and

enabling economies of scale. In parallel, technology demonstration campaigns are essential to build confidence among industrial emitters. By showcasing the performance stability of bio-derived CaCO₃ sorbents under real operational conditions, these campaigns can accelerate adoption and foster partnerships. Demonstrations should emphasize comparative advantages over conventional sorbents, including cost-effectiveness and sustainability credentials. Finally, community-facing communication programs must be developed to strengthen social acceptance. Public perception often represents a critical barrier to industrial projects; therefore, transparent communication highlighting waste reduction, carbon capture benefits, and local economic gains can counteract opposition and enhance legitimacy.

Actions to address weaknesses

Current weaknesses relate primarily to governance complexity, quality variability, and financial constraints. To overcome these, a Symbiosis Facilitation Initiative (de Araujo et al., 2011; Sellitto et al., 2025) should be created. This initiative would operate under a joint governance model involving mussel farms, industrial actors, research institutions, and public authorities. Its functions would include mediating contracts, establishing risk-sharing arrangements, and providing legal and managerial expertise to less-experienced stakeholders, under the strategic design of diffused eco-park (Scafà et al., 2018). By institutionalizing coordination, the initiative can reduce transaction costs and enhance trust.

Quality control represents another critical weakness. The introduction of standardized protocols for sampling, testing, and contamination removal is imperative. Harmonization will ensure consistent feedstock quality and operational reliability. Digital tracking systems should be implemented to record shell origin and composition, enabling full traceability. Additionally, pre-processing stations can homogenize shell material before CaL application, mitigating variability and contamination risks. Financial barriers can be addressed through green financing instruments. Blended finance models, combining public-private partnerships, green bonds, and ESG investment funds, can mobilize capital for infrastructure development. Carbon capture benefits should be monetized via carbon credit schemes, while credit guarantees can incentivize SME participation in the value chain.

Actions to capture opportunities

The initiative aligns closely with global sustainability agendas, creating opportunities for resource mobilization and stakeholder engagement. Explicitly linking outcomes to SDGs and ESG frameworks will enhance attractiveness to investors and public agencies, positioning the project within broader climate and circularity narratives. Accessing EU innovation grants and regional cohesion funds represents another opportunity, as demonstrated by recent programmes (e.g., Chowdhury & Ehimen, 2022). Programs targeting industrial decarbonization, blue economy development, and circular value chains are particularly relevant. Proactive engagement with funding bodies can secure financial support for pilot projects and scale-up phases. Finally, workforce development is essential to sustain long-term operations. Local retraining programs, in collaboration with vocational institutes, can reskill workers from declining industrial sectors for roles in shell processing, quality con-

trol, and CaL operation. This approach not only addresses labour shortages but also reinforces the socio-economic legitimacy of the initiative.

Actions to mitigate threats

External threats include spatial mismatches, regulatory uncertainty, and market volatility. To mitigate these, spatial mapping and prioritization should identify symbiosis hotspots where mussel farms, shell waste streams, and CO₂ emitters converge. Early deployment in these areas will maximize efficiency and minimize logistical costs. Regulatory risk can be reduced through policy engagement. Advocacy efforts should aim to secure long-term stability by clarifying industrial symbiosis definitions in legislation, promoting stable carbon pricing mechanisms, and requesting subsidies for circular feedstock-based carbon capture. Finally, market volatility necessitates flexible business models. Long-term supply contracts for CaCO₃ can stabilize revenue streams, while diversification into alternative applications beyond CaL, such as construction materials or specialty chemicals (Hart, 2020) can buffer demand fluctuations. Further refining of CaCO₃ is also an option (Roşioru, 2023). Risk-sharing mechanisms should be incorporated to protect SMEs from price shocks, ensuring resilience across the value chain.

8. Conclusion and future research trajectories

As we demonstrated in previous pages, the integration of mussel shell waste into calcium looping (CaL) systems represents a novel circular economy approach with significant environmental and industrial potential. Mussel shells, rich in calcium carbonate (CaCO₃), are generated in large volumes from aquaculture and foodservice sectors. Through pre-treatment and chemical purification, high-purity CaCO₃ can be extracted and used to produce solid sorbents for CaL systems, which capture CO₂ from industrial flue gases. This closed-loop model not only mitigates waste disposal issues, but also contributes to scalable decarbonization. Calcium looping has reached a Technology Readiness Level (TRL) above 7, enabling integration with cement, steel, and energy sectors. MATSHELL project has advanced purification protocols tailored to shell origin, enhancing process adaptability and product consistency.

However, challenges persist. First, variability in shell composition and contamination complicates CaCO₃ standardization, requiring robust quality control. Second, mussel producers often lack familiarity with secondary markets, creating hesitancy in forming interdependent supply chains, with potentially disruptive effect on the symbiotic network, as in the Galician experience. Third, implementing the symbiosis initiative demands significant capital investments. Public-private collaboration, particularly with banking institutions, is essential to unlock green financing and environmental remuneration mechanisms, such as carbon credits.

On the other hand, geographic proximity between mussel farms and industrial emitters facilitates symbiotic partnerships, improving logistics and public acceptance, especially in coastal urban areas. In this regard, the public sector can play a highly significant role by establishing eco-industrial parks or by managing industrial areas in an integrated manner, thereby fostering the co-location of firms and enabling resource exchanges. Such exchanges should be appropriately identified and

supported through the definition of a clear regulatory framework, particularly with respect to the distinction between by-products and waste. This regulatory differentiation is fundamental, as it allows a residual stream to be classified as a “by-product” rather than as “waste” (e.g. Article 184-bis of Legislative Decree 152/06 in Italy), thus facilitating its direct reuse without the need for complex and burdensome bureaucratic procedures. From this perspective, the primary role of public authorities lies in removing existing barriers (“barrier busting”) and in creating the infrastructural and regulatory conditions (“market creating”) that make industrial symbiosis a viable and scalable practice within a more agile overall organizational framework. At the same time, beyond facilitating and promoting the development of eco-industrial parks to ensure a more coherent and integrated supply structure, it is equally important to simultaneously activate market dynamics through policy measures capable of stimulating demand for outputs and derivatives generated by symbiotic processes. In this sense, the advantage offered by this case study is particularly relevant, as the products envisaged as outcomes of the symbiotic process would directly support green practices and public policies. This creates the opportunity to identify and mobilize dedicated funding streams specifically targeted at initiatives of this kind.

Building on the limitations we recognise in this work, several avenues for future research emerge, which, in our opinion, could appeal to a wider audience of researchers and practitioners interested in developing the proposed model. First, the interaction between the proposed symbiotic model and real market dynamics requires a period of adaptation and gradual penetration. Early-stage pilot hubs may face operational inefficiencies, unstable supply chains, or limited producer engagement, potentially jeopardizing the short-term profitability and long-term viability of the system. This calls for deeper investigation into the evolutionary pathways of new entrants within industrial symbiosis contexts. Second, the geography of the symbiotic system introduces constraints linked to local cultural, administrative, and infrastructural barriers. These may prevent the emergence of optimal hubs, instead favoring only those regions where institutional or bureaucratic conditions happen to be more permissive, even if sub-optimal in terms of logistics or industrial proximity. Future research should therefore include a systematic analysis of geographic and institutional barriers specific to mussel shell-based CaL systems. Finally, the symbiotic initiative may clash with the generational and organizational dynamics of mussel-producing firms, many of which are family-run and characterized by path dependency, risk aversion, and intra-firm decision-making norms. These internal dynamics can hinder innovation adoption, delay collaboration agreements, or create asymmetric participation among producers. A dedicated research stream examining family business behavior within circular economy and industrial symbiosis frameworks would therefore be highly beneficial.

Acknowledgments

We would like to express our sincere gratitude to Prof Gianluca Sarà and Dr Maria Cristina Mangano, the scientific coordinators of the MatShell project, for involving us in this stimulating and intellectually rewarding initiative. Their leadership and openness have created a fertile environment for collaboration, allowing us to

engage with colleagues from a wide range of disciplines. The interdisciplinary exchanges fostered within the project have provided valuable perspectives and generated insightful discussions that significantly enriched our work and understanding.

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