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Determinants and strategies of sustainability-driven innovation. A longitudinal case study of the mining industry

Abstract: While prior research has examined the determinants and outcomes of sustainability-driven innovation, the strategic interplay between leveraging internal capabilities and forming external collaborations remains underexplored, particularly in resource-intensive industries where dynamic capabilities play a pivotal role in balancing proprietary innovation with systemic partnerships. This study investigates how firms navigate the strategic dilemma of pursuing sustainability-driven innovation internally versus through external collaborations. Drawing on a longitudinal case study of ALPHA, a global mining leader, the research explores how internal capabilities and partnerships drive innovation in areas like low-carbon technologies, renewable energy, and circular economy practices. Findings highlight the trade-offs between control and resource sharing, emphasizing the role of dynamic capabilities in balancing proprietary innovation with systemic collaboration. This study contributes to the literature on sustainability-driven innovation by providing insights into the strategic responses to sustainability imperatives and offering practical implication for firms managing similar challenges.

Keywords: *Sustainability-driven innovation, strategic trade-offs, mining industry*

1. Introduction

More and more, firms are challenged on their actions and need to scrutinize their impact on the environment (Ferraro et al., 2015; Callagher et al., 2022). Dealing with these challenges is widely acknowledged to necessitate specific innovations (Colquitt & George, 2011). Transforming traditional innovation into sustainability-driven innovation requires a reorientation of priorities to align technological advancements with environmental and social objectives (Hall, Daneke, & Lenox, 2010). The later stands out because it embeds sustainability

objectives into technological, organizational, and strategic advancements (Adams et al., 2016). Even more, firms do not pursue traditional and sustainability-driven innovation with the same strategic approach (Demirel & Kesidou, 2011; Hojnik & Ruzzier, 2016; Rennings, 2000). For developing sustainability-driven innovation, firms depend on a larger and specific resources portfolios like R&D and technical expertise, that need to strategically be align with firm's strategy (Horbach et al., 2012; Cuerva et al., 2014). Externally, regulatory frameworks, consumer demand, and technological advancements play a major role, supported by government policies and market dynamics that align economic and environmental goals (Porter & Van der Linde, 1995; Jaffe et al., 2005; Kemp & Pearson, 2007), pushing firms to even more develop sustainability-driven innovation.

Despite its promise, sustainability-driven innovation faces challenges (Hojnik & Ruzzier, 2016; Rennings, 2000; Ghisetti & Pontoni, 2015). Internally, high costs, resource limitations, and organizational barriers can slow progress (Demirel & Kesidou, 2011; Cuerva et al., 2014; Horbach et al., 2012), while externally, firms must navigate regulatory complexities, international collaboration hurdles, and evolving market demands (Jaffe et al., 2005; Kemp & Pearson, 2007; Del Río et al., 2016). Collaborative partnerships with universities, suppliers, competitors and other stakeholders offer solutions by pooling expertise and resources (Belderbos et al., 2004; Triguero et al., 2013; Fernandez et al., 2014), though these arrangements bring risks such as knowledge leaks and strategic misalignment (Rennings, 2000; Beuter Júnior et al., 2019; Ma et al., 2022).

While extensive literature examines sustainability-driven innovation determinants (Adams et al., 2016; Horbach et al., 2012; Ghisetti & Pontoni, 2015), less is known about how firms in resource-intensive and highly regulated industries develop sustainability-driven innovation. Existing research often isolates internal development and external collaborations (Demirel & Kesidou, 2011; Chesbrough, 2003; Triguero et al., 2013), leaving a gap in

understanding how these strategies are integrated to address complex sustainability challenges. It is important to fulfil this gap because successfully advancing sustainability-driven innovation might require balancing internal development with external partnerships. Indeed, firms must carefully address these challenges to capitalize on opportunities and remain competitive (Porter & van der Linde, 1995; Gnyawali & Park, 2011; Hojnik & Ruzzier, 2016) while contributing to environmental and social sustainability (Rennings, 2000; Kemp & Pearson, 2007; Ekins, 2010). Therefore, in this study, we wonder of how firms can develop sustainability-driven innovation strategy?

To address this question, we examine ALPHA, a global mining leader with robust R&D capabilities and a strong sustainability agenda. Through a qualitative, longitudinal single case study, we explore how ALPHA advances sustainability-driven innovations via internal projects and external collaborations. Drawing on 30 semi-structured interviews and secondary data, we highlight the key determinants, benefits, and challenges of both approaches.

The findings reveal three key insights. First, sustainability-driven innovation is propelled by regulatory imperatives, market pressures, and stakeholder demands, requiring firms to navigate a complex interplay of internal and external determinants. Second, internal projects offer greater control and alignment with long-term goals but face challenges in resource intensity and scalability. Third, collaborative projects enable firms to address systemic challenges beyond internal capacities by leveraging partnerships with suppliers, competitors, and academic institutions. This dual strategy of "make" and "ally" highlights the strategic trade-offs and synergies inherent in sustainability-driven innovation.

This article contributes to the literature on sustainability-driven innovation and strategic management in three ways. First, it provides new insights into the determinants of sustainability-driven innovation, highlighting both established factors like regulatory mandates (Horbach et al., 2012; Porter & van der Linde, 1995; Ghisetti & Rennings, 2014) and emerging

determinants such as cumulative environmental impacts and regional collaboration needs. These findings enrich the current understanding of what propels sustainability-driven innovation in resource-intensive industries (Rennings, 2000; Triguero et al., 2013; Ekins, 2010). Second, it challenges the traditional view of internal and external innovation strategies as distinct pathways (Chesbrough, 2003; Gnyawali & Park, 2011; Parmigiani, 2007) by demonstrating their coexistence as complementary approaches (Fernandez et al., 2021). While the existing research have rather show that firms need to make or ally (Fernandez et al., 2021), this study show that these two logics need to co-exist. This coexistence is essential because different project characteristics necessitate drawing on both internal projects for control, process optimization and immediate benefits, and external projects for access to specialized expertise, sharing the risk associated to innovation development and scalability. Third, it underscores the organizational ability to balance these dual approaches, by illustrating how firms develop the capacity to integrate internal development with collaborative efforts to address sustainability challenges effectively (Teece, Pisano, & Shuen, 1997; Eisenhardt & Martin, 2000; Ma et al., 2022).

2. Literature review

2.1. Specificities and determinants of sustainability-driven innovation

2.1.1. Specificities of sustainability-driven innovation

Sustainability-driven innovation has garnered significant scholarly attention, but a standardized definition remains elusive (Horbach et al., 2012). Terms like eco-innovation, green innovation, and sustainable innovation are often used interchangeably (Leal-Millán et al., 2017; Kemp & Pontoglio, 2007), reflecting firms' environmental commitments. However, the lack of common terminology complicates distinguishing these concepts. While "green," "eco," "environmental," and "sustainable" share foundational principles, they differ in scope and objectives, warranting deeper exploration (see Table 1).

INSERT TABLE 1 ABOUT HERE

A clearer distinction emerges when examining the focuses of green innovation and eco-innovation. Indeed, green innovation emphasizes products or processes aimed at pollution prevention and waste reduction, with a narrower focus on environmental risk minimization (Eiadat et al., 2008). Kemp and Pontoglio (2007) highlight the need for a lifecycle approach to reduce harm throughout a product's lifespan. In contrast, eco-innovation prioritizes environmental outcomes, positioning itself as a subset of sustainability-driven efforts. Ekins (2010) distinguishes eco-innovation by its balance of environmental and economic performance, while "environmental innovation" often addresses only ecological concerns. Schiederig and colleagues (2012) emphasize eco-innovation's role in mitigating ecological degradation through waste minimization and ecosystem protection.

Building on this, sustainable innovation expands the perspective by integrating environmental, social, and economic benefits under the triple bottom line (Szekely & Strebel, 2013; Adams et al., 2016). This approach simultaneously addresses multiple sustainability dimensions. Kemp and Pearson (2007) define eco-innovation as any novel process, product, or organizational structure that minimizes environmental risks and resource use across its lifecycle. Álvarez et al. (2014) extend this by highlighting waste minimization and ecosystem protection. This lifecycle and systems perspective further reinforces sustainability-driven innovation's transformative potential, ensuring sustainability at every stage of innovation. It also underscores sustainability-driven innovation's commitment to systemic change and value creation across ecological, social, and financial dimensions (Elkington, 1997).

In this context, this research adopts Kemp and Pearson's (2007) lifecycle-centric definition of eco-innovation, expanding it to include sustainability-driven innovation's

systemic and inclusive attributes. By emphasizing novelty, and environmental risk reduction, this study is focused on understanding key determinants of sustainability-driven innovation.

2.1.2. Determinants of sustainability-driven innovations

Existing research on innovation identifies internal and external determinants as critical to the adoption of sustainability-driven innovation (Horbach, 2008). By relying on Resource-Based View, the development of sustainability-driven innovation need firm's unique resources and capabilities to establish competitive advantages (Jové-Llopis & Segarra-Blasco, 2018). Core competencies, including R&D investment and technical expertise, also underpin successful initiatives (Cainelli et al., 2008; Antonioli & Mazzanti, 2009). These efforts must align strategically with organizational assets (Bossle et al., 2016). Firm-specific factors, such as size, age, and sector, also influence adoption, with larger firms leveraging resources and smaller firms driving agility-based innovation (Rehfeld et al., 2007; Francoeur et al., 2017).

Externally, regulatory mandates strongly motivate firms to align with environmental standards (Porter & Van der Linde, 1995; Ghisetti & Rennings, 2014). Policies like command-and-control regulations and subsidies reduce costs while boosting competitiveness. Market dynamics, including rising consumer demand for sustainable products and turnover expectations, push firms to innovate (Horbach et al., 2012; Ghisetti & Quatraro, 2013). Simultaneously, technological advancements and collaborative efforts fuel innovation by providing technical support (Rehfeld et al., 2007; Kammerer, 2009; Ghisetti & Pontoni, 2015).

In the nutshell, developing sustainability-driven innovation can allow firms to use their strategic resources to enhance sustainability and profitability, reinforcing their market position as leaders in environmentally conscious industries (Ghisetti & Pontoni, 2015) but it can also be a response to regulatory and environmental pressure. This raises the question of how firms can strategically advance these innovations.

2.2. How to develop sustainability-driven innovations?

2.2.1. Challenges in developing sustainability-driven innovations

The development of sustainability-driven innovation is fraught with challenges for firms (Chiambaretto et al., 2024). Developing in-house sustainability-driven innovations demand extensive resource portfolios, including financial and intellectual capital, as well as specific knowledge essential for their development (Leyva-De la Hiz et al., 2019). These innovations often require greater investments and are inherently riskier than traditional innovations due to uncertainties in their outcomes (Aragon-Correa, 1998; Xie et al., 2019; Zhao et al., 2023). To justify these higher costs, sustainability-driven innovations must deliver significant impact, often necessitating radical or disruptive approaches to achieve meaningful environmental and societal benefits (Rouyre et al., 2024).

These internal challenges are further compounded by organizational barriers. Almodovar et al. (2016) highlight critical issues such as a lack of motivation tied to insufficient short-term profit incentives, limited capital for long-term projects, and knowledge gaps that disadvantage firms relative to established competitors. Furthermore, access to critical technological knowledge remains a major obstacle, especially for firms in environmentally conscious industries (Jakobsen & Clausen, 2014). High upfront costs amplify these difficulties, requiring firms to balance environmental goals with economic feasibility (Hojnik et al., 2016).

External challenges also present significant hurdles. Firms developing sustainability-driven innovations face compliance pressures from evolving standards and restrictions (Del Río et al., 2016). Regulatory requirements act as both a catalyst and a constraint, compelling firms to align with legislative mandates while navigating complex international markets and cross-border collaborations (Del Río et al., 2016). Additionally, multinational operations often contend with foreign regulations, limited access to international funding, and the logistical complexities of effective collaboration with overseas institutions. Together, these external factors add considerable complexity to the development process.

Internal development of sustainability-driven innovations presents unique and substantial demands, particularly in resource-intensive industries, where it is crucial to advance sustainability-driven innovation while ensuring competitiveness (Ma et al., 2022; Eiadat et al., 2008; Demirel & Kesidou, 2019; Adams et al., 2016; Ghisetti et al., 2017). Such innovations necessitate extensive investments in R&D, advanced technologies, and specialized human capital, which can strain organizational resources and capabilities (Rashid et al., 2022). These requirements are exacerbated in industries facing rapid technological advancements, where the lifecycle of sustainability solutions often outpaces the firm's ability to adapt to emerging environmental regulations and shifting market demands (Hart, 1995; Porter & van der Linde, 1995; Kunapatarawong & Martínez-Ros, 2016).

2.2.2. How to address sustainability-driven innovation challenges: the key role of external collaborations?

To navigate the challenges of developing sustainability-driven innovation, firms increasingly rely on external inter-organizational collaborations (Melander & Ardisson, 2022; Rouyre et al., 2024). Such collaboration provide access to specialized expertise and complementary resources through alliances with suppliers, universities, government bodies and competitors (Chesbrough, 2003; Roh et al., 2023; Fernandez et al., 2014). By integrating external knowledge, these external inter-organizational collaborations accelerate innovation cycles while distributing costs and risks, making them particularly advantageous for capital-intensive sustainability-driven innovation projects (Chistov et al., 2023). In fast-paced sectors with rigorous environmental standards, inter-organizational collaboration offers firms swift access to expertise and networks critical for agility and compliance (Roh et al., 2023).

Despite their advantages, external inter-organizational collaborations for sustainability-driven innovation bring inherent complexities. They may lower costs and expand capabilities but introduce risks such as intellectual property exposure, potential misalignment of strategic

objectives, and diminished process control (Kogut & Zander, 1992). Strategic complexities include knowledge spillover risks, where shared innovations inadvertently benefit competitors, diluting competitive advantage (Rennings, 2000; Jaffe et al., 2005). Misaligned priorities and the need to safeguard intellectual property can create friction, necessitating dynamic capabilities to align external knowledge with the firm's strategic goals (Beuter Júnior et al., 2019; Ma et al., 2022).

Moreover, when collaborating with stakeholders for sustainability-driven innovation, firms face the "double externality" problem, where societal benefits of environmental innovations extend beyond the firm, potentially reducing competitive gains (Rennings, 2000). To mitigate this, firms must cultivate reciprocal collaborations that align strategic goals and ensure mutual benefits. Effective collaboration should not only advance the firm's objectives but also strengthen broader institutional frameworks (Ghisetti & Rennings, 2014; Junquera et al., 2012). While external inter-organizational collaborations are essential for addressing many of the challenges associated with sustainability-driven innovation, they also raise important questions about the conditions under which firms should rely on their internal capabilities versus external partnerships. The trade-offs and synergies between these approaches remain an open area of exploration.

2.3. Research Gap

Despite growing interest in sustainability-driven innovation, management research has yet to fully address how firms choose between leveraging internal capabilities and forming external inter-organizational collaborations. While studies provide insights into the determinants and outcomes of sustainability-driven innovation (Horbach, 2008; Kemp & Pontoglio, 2007; Porter & Van der Linde, 1995) and the benefits of external partnerships (Chesbrough, 2003; Ghisetti & Rennings, 2014), the interplay between these approaches remains underexplored. Existing research does not clarify how firms decide between in-house innovation and external alliances,

or the trade-offs involved. This leaves open the question of how firms can develop sustainability-driven innovation strategy?

3. Method

3.1. Research design

We used a longitudinal single case study to explore how firms drive sustainability through internal projects or external collaborations (Eisenhardt, 1989; Eisenhardt & Graebner, 2007). This method, suited for complex, context-dependent phenomena, provides insights into strategic decision-making (Siggelkow, 2007; Yin, 2009). It is particularly relevant to the mining sector, where interdependencies, regulations, and resource constraints shape strategies (Scalera et al., 2014; Welch & Piekkari, 2017).

We adopted an embedded case study design (Yin, 2012) to compare internal projects and external collaborations in sustainability-driven innovation, highlighting strategic determinants, constraints, and outcomes (Parmigiani, 2007; Puranam et al., 2013). Focusing at the corporate level highlights strategic priorities, resource allocation, and stakeholder demands shaping sustainability-driven innovation, as well as the trade-offs between internal projects and external collaborations in resource-intensive industries (Porter & Kramer, 2011; Teece, 2007; Demirel & Kesidou, 2019; Rashid et al., 2022).

3.2. Empirical context and case presentation

The mining industry's environmental impact, capital intensity, and systemic challenges make it a compelling context for studying sustainability-driven innovation. Pressures from energy use, resource extraction, and regulations push firms toward innovative solutions aligned with environmental and social goals. Trends like circular economy principles, supply chain decarbonization, and electrification underscore the need for advanced technologies and collaboration to address climate change and resource scarcity.

ALPHA, a global mining leader operating on six continents, exemplifies sustainability-driven innovation. Its internal R&D drives breakthroughs like carbon-neutral aluminum production, while collaborations with academia, technology providers, and competitors address systemic challenges such as water management, low-carbon steel, and renewable energy integration. These efforts highlight ALPHA's strategic adaptability and the potential of sustainability innovation in resource-intensive industries.

3.3. Data collection

Adhering to qualitative research principles (Eisenhardt, 1989; Yin, 2012; Gibbert et al., 2008), the study utilized 30 semi-structured interviews and extensive secondary data to ensure depth and minimize bias (Eisenhardt, 1989; Yin, 2009) (See Table 2).

INSERT TABLE 2 ABOUT HERE

Data were collected through 60-minute interviews with executives, R&D experts, and project managers, capturing strategic decisions and project-level innovations. These interviews produced 450 pages of transcripts, supplemented by detailed notes when recording was unavailable.

Secondary data comprised 500 pages of industry reports, corporate sustainability documents, and media coverage. Reports from the International Council on Mining and Metals (ICMM) highlighted global trends and regulations, while ALPHA's sustainability reports detailed decarbonization, resource efficiency, and circular economy initiatives. Technical reports covered innovations like low-emission equipment and renewable energy. Combined with primary data, these sources provided a comprehensive view of internal projects and external collaborations in sustainability-driven innovation.

3.4 Data analysis

Data were analyzed using systematic coding methods (Miles & Huberman, 1994; Gioia et al., 2013) with QualCoder software to organize and examine primary and secondary sources. An iterative approach linked data to theoretical frameworks, supported by team discussions for triangulation and validation (Eisenhardt, 1989).

Coding identified first-order concepts from interviews and secondary data, grouped into second-order themes like "Biodiversity and technological advancements" and "Process optimization and asset efficiency". Aggregate dimensions, such as "Determinants of Sustainability-Driven Innovation," linked patterns to theoretical constructs (see Figure 1).

INSERT FIGURE 1 ABOUT HERE

To limit interpretive bias, triangulation ensured validity and reliability (Miles & Huberman, 2003; Hayashi et al., 2019). External data contextualized collaborations, while internal documents validated performance metrics. Interview claims were corroborated with metrics and documented outcomes, enhancing robustness through iterative analysis.

The coding structure was refined through researcher triangulation and a devil's advocate strategy (Rerup & Feldman, 2011; Estrada et al., 2016b). External team members critically evaluated codes, while cross-validation with corporate reports and industry publications ensured themes aligned with interview narratives and broader industry contexts.

4. Findings

The mining industry, renowned for its resource intensity and environmental impact, faces mounting pressure to develop sustainability-driven innovations. While historically slow to innovate, the industry's inherent dependence on natural resources necessitates a paradigm shift toward sustainability-driven innovation. In this study, we highlight the complexity of steering sustainability-driven innovation by relying on internal projects and external inter-organizational collaborations from a leading mining company.

4.1. Multi-faced determinants of sustainability-driven innovation for ALPHA within the mining industry

4.1.1 Regulatory imperatives and policy incentives

Mining firms pursue sustainability-driven innovation to comply with strict global regulations. In Europe, directives like the Industrial Emissions Directive (2010)[1] and Waste Framework Directive (2008)[2] mandate cleaner technologies and circular economy practices. Australia's Environment Protection and Biodiversity Conservation Act (1999)[3] focuses on biodiversity and resource sustainability, while Canada's Environmental Protection Act (1999)[4] emphasizes pollution prevention. The 2015 Paris Agreement[5] intensifies global pressure for low-carbon technologies and net-zero goals. South Africa's Mine Health and Safety Act (1996)[6], alongside international standards like the UN Guiding Principles on Business and Human Rights (2011)[7] and ICMM Mining Principles (2020)[8], promotes ethical and sustainable mining practices.

For ALPHA, meeting emissions reduction targets, waste management directives, and water usage regulations is integral to its operations. ALPHA achieves this by sensing emerging regulatory trends, investing in innovative low-carbon technologies, and forging strategic partnerships to address resource constraints. These efforts enable ALPHA to adapt its operations while maintaining compliance and advancing its sustainability goals. For example, the firm proactively integrates renewable energy solutions into its processes and deploys advanced waste management systems to exceed environmental standards. Thus, ALPHA transforms compliance into an opportunity to enhance operational efficiency and strengthen its

[1] EU - Industrial Emissions Directive (2010/75/EU) - https://eur-lex.europa.eu/eli/dir/2010/75/oj/eng
[2] EU - Waste Framework Directive (2008) - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098
[3] Australian Government - Environment Protection and Biodiversity Conservation Act - https://www.legislation.gov.au/C2004A00485/latest/text
[4] Canada's Environmental Protection Act (1999) - https://laws-lois.justice.gc.ca/eng/acts/c-15.31/FullText.html#:~:text=Declaration,sustainable%20development%20through%20pollution%20prevention
[5] Paris Agreement 2015 - https://unfccc.int/process-and-meetings/the-paris-agreement
[6] South African Government - Mine Health and Safety Act (1996) - https://www.gov.za/documents/mine-health-and-safety-act
[7] UN Guiding Principles on Business and Human Rights (2011) - https://www.ohchr.org/sites/default/files/documents/publications/guidingprinciplesbusinesshr_en.pdf
[8] ICMM Mining Principles (2020) - https://www.icmm.com/en-gb/our-principles/mining-principles/mining-principles

competitive position by aligning its objectives with regulatory requirements and fostering collaboration with external stakeholders.

> *"Our industry has always been scrutinized for its environmental footprint, but the regulatory landscape has evolved into a game-changer." - Compliance officer at ALPHA.*

Beyond compliance, policy incentives are also a common practice in the mining industry. Firms can have access to tax credits and grants to reduce financial risks of innovation. ALPHA leverages these incentives to accelerate sustainability-driven innovation by identifying key areas of investment and fostering cross-sector collaborations. Aligning internal initiatives such as carbon capture technologies and renewable energy integration with external partnerships allows the firm to maximize the impact of policy-driven funding. Even more, such incentives also help ALHA to align innovations such as green steel and renewable energy with long-term sustainability goals.

> *"Australian cooperative research policies have streamlined cross-sector collaborations by creating clear legal and funding frameworks, making it easier to pursue sustainability-driven innovation." - Sustainability director at ALPHA*

4.1.2. Strategic priorities: biodiversity and technological advancements

Biodiversity preservation is a vital aspect of sustainability-driven innovation in mining, emphasizing the need to mitigate impacts on ecosystems. Companies adopt biodiversity action plans, including habitat restoration, conservation offsets, and minimizing land disturbances. Examples include creating nature reserves near mining sites, reforesting affected areas, and funding research on restoring local flora and fauna. Reusing mine tailings for construction materials further reduces the environmental footprint of mining waste.

For ALPHA, biodiversity initiatives are deeply integrated into corporate strategy, combining measurable outcomes with innovation. For example, it leverages nature-based solutions, such as reforestation and water cycle stabilization, alongside advancements in water treatment technologies to address both operational needs and ecosystem dependencies.

"A sustainability-driven innovation could mean preserving a forest 10 kilometers away to stabilize water budgets at a mine site. It's about protecting dependencies like water cycles, which are directly tied to biodiversity." – Business development at ALPHA

The firm's initiatives also reflect a broader industry shift beyond policy compliance, integrating advanced technologies to align sustainability goals with innovation. Technological advancements are pivotal in minimizing environmental impact while enhancing efficiency and profitability. Examples include autonomous electric haul trucks and drones for site monitoring, which reduce fuel consumption and emissions while improving safety. Advanced mineral processing technologies, such as waterless ore processing and bioleaching, significantly cut water usage and chemical waste. Electrified mining fleets for resource optimization further demonstrate how ALPHA leverages technology to address environmental challenges.

"Technological advancements like electrification for large trucks are critical in reducing emissions across industries. However, infrastructure costs remain a significant barrier." – R&D manager at ALPHA

Through the integration of water management technologies and digital tools for emission tracking, ALPHA strengthens its capacity to adapt and innovate in response to changing environmental and market pressures.

4.1.3. Alignment with shareholders demands for ESG requirements

Firms, particularly in resource intensity and environmental impact industries like mining, are increasingly transforming corporate strategies to integrate environmental, social, and governance (ESG) principles. For the mining sector, this shift is driven by growing demands from investors, local communities, and NGOs for shared value approaches that incorporate social and environmental considerations into operations.

"We can't just extract resources and leave. Our communities expect us to leave behind a positive legacy." – Mining engineer at ALPHA

The firm actively engages with stakeholders to identify community needs, embedding these insights into sustainability initiatives and operational planning. By cultivating relationships with local communities and leveraging stakeholder feedback, ALPHA tailors its strategies to

address societal concerns effectively. The company's proactive approach includes aligning operations with societal expectations and anticipating emerging demands for transparency and accountability.

> *"Stakeholders expect mining companies to contribute to societal survival, aligning with the new economy of trust and sustainability." – Compliance officer at ALPHA*

These efforts highlight ALPHA's ability to adapt operations to balance business goals with societal impact, ensuring resilience in a rapidly evolving industry. Investors increasingly link capital allocation to ESG performance, critical for the mining sector. For example, BlackRock pressures firms to disclose climate risks and adopt decarbonization strategies[9], while Norway's Pension Fund excludes companies with harmful environmental practices[10]. ESG-focused funds, such as the Vanguard ESG International Stock ETF[11], prioritize firms investing in renewable energy and low-impact technologies. Similarly, ICMM Principles, backed by major investors, promote improved water stewardship, emissions reduction, and community development.

In the case of ALPHA, investor demands have driven the development of external projects with indigenous communities and the integration of stakeholder-focused practices. By incorporating local labor into operations and investing in educational initiatives, ALPHA aligns its strategies with societal expectations from the value chain while enhancing stakeholder trust.

> *"Investors aren't just asking about returns anymore; they're asking about carbon footprints and community impact."* - *Compliance officer at ALPHA*

Finally, the global emphasis on decarbonization and resource efficiency has increased demand for green steel and circular economy practices, prompting firms like ALPHA to reimagine operations to align with the sustainability objectives of downstream stakeholders. End-users in

[9] BlackRock – TCFD Report 2023 - https://www.blackrock.com/corporate/literature/continuous-disclosure-and-important-information/tcfd-report-2023-blkinc.pdf
[10] Norges Bank Investment Management - https://www.nbim.no/en/news-and-insights/the-press/press-releases/2016/exclusion-of-coal-companies-from-the-fund
[11] Vanguard approach to ESG - https://www.vanguard.co.uk/content/dam/intl/europe/documents/en/our-approach-to-esg__uk-pro.pdf

sectors like automotive and construction increasingly require sustainable materials to meet their environmental commitments, driving ALPHA to innovate and adapt. For example, the firm aligns its low-carbon strategies with client expectations by collaborating on solutions that reduce Scope 3 emissions and decarbonize the supply chain.

> *"Our automotive and construction clients demand lower-carbon inputs, and we must adapt to remain competitive." - Project manager at ALPHA.*

4.2. ALPHA's internal sustainability-driven innovation projects

4.2.1. A multiplicity of internal sustainability-driven innovation projects

ALPHA's approach to sustainability-driven innovation is characterized by its ambitious internal initiatives (see Table 3), which focus on reducing emissions, enhancing resource efficiency, and adopting breakthrough technologies. Through targeted investments and operational advancements, ALPHA has embedded sustainability into its core practices, setting industry benchmarks for environmental responsibility while addressing climate challenges.

INSERT TABLE 3 ABOUT HERE

Emissions reduction lies at the core of ALPHA's sustainability strategy, exemplified by a series of impactful initiatives. In 2020, the company launched **INT-001**, a major internal program aimed at cutting both absolute and intensity emissions, establishing a strong alignment with global climate objectives and forming the cornerstone of its decarbonization efforts. This was complemented by **INT-002**, which deployed renewable energy solutions such as solar power and energy storage systems, reducing fossil fuel dependency and enhancing energy resilience in mining operations. Building on these advancements, **INT-003**, introduced in 2021, focused on R&D for low-carbon industrial processes, piloting scalable solutions to address emissions in core operations. By 2023, ALPHA initiated **INT-004**, a pilot project exploring biofuel feedstocks as alternatives to traditional diesel, further curbing emissions while enhancing domestic energy security. These efforts underscore ALPHA's holistic and

innovative approach to tackling emissions through both technological advancements and renewable energy integration.

ALPHA's focus on sustainability also extends to securing critical materials and supporting the energy transition. In 2024, the company executed **INT-006**, a strategic acquisition to expand its capabilities in producing materials essential for electrification and renewable energy systems. This was complemented by **INT-007**, a venture investment in innovative startups focused on sustainable resource extraction. Through this initiative, ALPHA validated cost-efficient, environmentally friendly extraction processes by initiating pilot projects that align with its sustainability goals.

4.2.2. A set of benefits of conducing internal projects

For ALPHA, the decision to pursue internal innovation reflects a focus on core business priorities, operational optimization, and proprietary knowledge. This approach allows ALPHA to align innovation efforts tightly with their organizational strategy, deliver immediate operational benefits, and maintain greater control over outcomes.

Strategic control for enhancing competitive advantage. The ability to exercise strategic control is pivotal in driving competitive advantage, particularly by prioritizing and integrating innovation into existing processes and assets. This focus on resource control enables firms like ALPHA to address business-specific challenges independently, minimizing external dependencies and safeguarding sensitive innovations. Leveraging proprietary knowledge, data, and in-house expertise allows ALPHA to deliver tailored solutions that set it apart in the market.

> *"The decision to keep projects internal often depends on their strategic importance and alignment with our core business. Internal teams allow us to prioritize specific objectives and maintain tighter control over outcomes." – Executive at ALPHA*

Internal innovation projects are designed to align closely with strategic business goals, enabling the company to develop unique competitive advantages because it helps ALPHA to

mitigate external risks. Indeed, by developing in-house such critical projects, ALPHA can control the ownership of intellectual property.

> *"Internal sustainability-driven innovation projects enable companies to develop unique competitive advantages by leveraging proprietary knowledge and resources. These projects often align closely with strategic business goals." – Project manager at ALPHA*

Process optimization and asset efficiency. Optimizing processes and enhancing asset efficiency are fundamental advantages of internal sustainability-driven innovation. Firms leverage proprietary data and operational insights to uncover opportunities that align efficiency improvements with sustainability objectives. This approach enables the tailoring of innovative solutions to meet specific organizational needs, ensuring targeted outcomes that address both environmental and operational goals.

> *"Internal projects help us optimize existing processes and assets while leveraging our proprietary data, which is critical for driving innovation tailored to our operational needs." – Project lead at ALPHA*

Internal initiatives often focus on reducing costs, minimizing energy use, and transitioning to renewable energy, directly improving operational efficiencies while meeting regulatory requirements. This focus is particularly impactful for large-scale operations, where even minor process improvements can yield substantial cost and environmental benefits. However, internal projects also involve higher ownership risks due to resource allocation and execution challenges.

> *"Internal sustainability-driven innovation projects focus on reducing costs, energy use, and transitioning to renewable energy. They often lead to direct operational efficiencies and are increasingly driven by regulatory requirements." – Operations lead at ALPHA*

Immediate and tangible benefits. Internal projects often deliver immediate and tangible benefits, particularly through enhanced operational efficiencies and strategic alignment. ALPHA's internal sustainability-driven innovation projects have been successful by leveraging intensive R&D activities and focusing on long-term objectives, such as the integration of well-structured R&D departments and their alignment with overall business

strategy. Indeed, such integration then allows ALPHA to quickly adapt and optimize existing processes for operational gains.

> *"Internal projects focus on specific, long-term organizational goals, benefiting from well-established R&D departments and better integration into overall business strategy." – R&D manager at ALPHA*

Internal development of sustainability-driven innovations offers opportunities but also poses significant challenges for a global mining leader like ALPHA. While it ensures control over intellectual property and alignment with strategic goals, ALPHA's experience underscores difficulties.

4.2.3. An array of challenges in internal projects

Resource intensity and financial constraints. Internal sustainability-driven innovation projects face significant challenges due to the substantial resource investments required. Developing green technologies or sustainable mining methods demands extensive capital expenditure, skilled talent, and long-term commitment. These resource demands include infrastructure upgrades such material adjustments, advanced equipment, and specialized expertise to address sustainability goals effectively. Indeed, for example projects like improving water usage efficiency face upfront costs, despite promising long-term savings.

> *"Innovating internally is like running a marathon uphill—we need substantial upfront investments, and the payoffs often take years to materialize" - Project lead at ALPHA*

The need for upfront investments often creates tension between immediate business priorities and long-term sustainability objectives. For instance, ALPHA's commitment to transitioning to electric mining fleets required not only purchasing expensive vehicles but also upgrading infrastructure to support electrification.

> *"Scaling internal projects often demands substantial resources and investment, creating challenges when aligning them with immediate business needs." – Manager at ALPHA*

Organizational silos and coordination complexities. ALPHA's internal sustainability-driven innovation projects span multiple continents, each operating under

distinct regulatory and operational contexts. This geographical separation complicates decision-making by creating organizational silos, which hinder communication and alignment across teams. These silos exacerbate coordination challenges as different regions and departments prioritize localized objectives over collective strategic goals. The lack of centralized alignment means that scalability often depends on additional resources and advocacy to integrate internal projects with broader company growth platforms.

> *"Aligning teams across different regions and time zones, each with their own priorities, can slow down innovation and dilute focus." – Director at ALPHA*

For example, the firm's efforts to develop a new waste management system in project INT-002 illustrate these coordination complexities. This initiative involved cross-functional teams from engineering, environmental compliance, and operations, each with competing priorities.

> *"While the environmental team pushed for ambitious recycling targets, the operations team was focused on minimizing costs. Balancing these priorities was a constant negotiation." – Project manager at ALPHA*

Technological and market uncertainties. Developing sustainability-driven innovations internally involves navigating significant technological and market uncertainties. ALPHA faces the inherent risk of investing in emerging technologies that may not scale effectively or deliver the anticipated environmental or economic benefits.

> *"Every new technology comes with unknowns; there's always the possibility that it won't scale effectively or meet regulatory standards." – Senior Engineer at ALPHA*

The rapid evolution of environmental regulations and volatile market dynamics exacerbate these challenges. For instance, ALPHA's investment in proprietary water recycling technology, initially innovative, required expensive modifications to comply with new regulatory standards. Additionally, fluctuations in commodity prices further complicate the financial viability of sustainability-driven projects.

> *"When market prices fall, it's harder to justify the high costs of green technologies, even if they're the right thing to do in the long term." – Manager at ALPHA*

Resistance to change and cultural barriers. Internal sustainability-driven innovation projects at ALPHA often encounter resistance, particularly when they challenge established practices or require cultural shifts. Efforts to embed sustainability into core operations were initially met with skepticism from middle management and frontline workers, often due to a lack of understanding of the long-term benefits. This resistance highlights the need for proactive efforts to align organizational culture with sustainability goals.

> *"The biggest challenge is changing management within the company. Even when projects show clear benefits, resistance often comes from the layers of bureaucracy, which delay or kill promising initiatives." – R&D expert at ALPHA*

ALPHA's focus on internal sustainability-driven innovation underscores the strategic importance of owning proprietary green technologies and aligning them with corporate objectives. However, this approach introduces significant challenges, including delays, cost overruns, and inefficiencies stemming from supply chain constraints and organizational silos. Logistical complexities and misalignment further escalate operational costs and hinder progress, highlighting the difficulties of integrating sustainability into mining operations.

4.3. ALPHA's external sustainability-driven innovation projects

4.3.1. Key characteristics of external projects[12]

ALPHA's commitment to sustainability-driven innovation is deeply embedded in its strategic collaborations (see Table 4) and partnerships, spanning industries and geographies. Recognizing the critical need to decarbonize their operations, ALPHA has engaged in joint ventures, challenges co-organized with competitors and partners, and alliances to catalyze transformative change. By working with key stakeholders such as industry leaders, startups, and governments, ALPHA has become a pioneer in sustainable industrial practices, delivering outcomes that redefine environmental responsibility in mining and resource production.

INSERT TABLE 4 ABOUT HERE

[12] For confidentiality purposes, the names of external partners of ALPHA have been changed.

One of ALPHA's most notable collaborations is **COL-001** a joint venture with Company BETA (a competitor), Company GAMMA (a tech partner), and Government OMEGA. This initiative seeks to eliminate greenhouse gas emissions in industrial processes, deploying zero-emission technology at a pilot facility and advancing sustainable production. Similarly, **COL-004**, a global competition involving Company ZETA (a competitor), Company PSI (a competitor), and Organization UPSILON, focuses on electrifying large-scale equipment to reduce emissions. These efforts show ALPHA's strategy of leveraging innovative partnerships to address some of the most carbon-intensive activities in resource extraction and processing.

Collaborations with other industry leaders further underscore ALPHA's commitment to sustainability. Through **COL-003**, a partnership with Company EPSILON (a supply chain partner), ALPHA has developed digital platforms and technologies that support circular ecosystems, including solutions such as microgrids and AI for decarbonization. The partnership with Company DELTA (a customer) under **COL-002** focuses on reducing emissions across the supply chain by implementing low-carbon solutions, while **COL-006**, a Memorandum of Understanding (i.e., MOU) with Company THETA (a customer), explores renewable inputs and low-carbon technologies for industrial processes. These initiatives highlight ALPHA's emphasis on combining diverse expertise to accelerate the transition to a low-carbon economy along the value chain.

ALPHA is also driving innovation through investments in groundbreaking technologies and strategic ventures. In **COL-008**, ALPHA partnered with SIGMA (a startup) to develop a waterless filtration technology for resource extraction, with plans to launch a pilot plant demonstrating cost-efficient and sustainable methods. Additionally, initiatives such as **COL-009**, a partnership with Company KAPPA (a competitor), aim to develop large-scale resource projects that support critical mineral supplies essential for renewable energy. Through **COL-**

010 and **COL-011**, ALPHA is collaborating with Company LAMBDA (a customer) and Company OMICRON (a supply chain partner) to integrate responsibly sourced materials into sustainable manufacturing and boost regional supplies of critical resources. These collaborations showcase how ALPHA's unified approach to sustainability-driven innovation creates shared value while advancing global decarbonization goals. For a global leader in the mining industry, partnerships and collaboration are not just optional strategies—they are essential mechanisms for driving sustainability-driven innovation. ALPHA has engaged in extensive collaborations with suppliers, competitors, research and governmental institutions to overcome challenges associated with sustainability-driven innovation and amplify its impact.

4.3.2. Large set of benefits in the collaboration

Access to specialized expertise and knowledge. One of the most significant contributions of partnerships to sustainability-driven innovation is the ability to access specialized expertise that complements ALPHA's internal capabilities. Developing sustainability-driven innovations often requires cutting-edge technologies and advanced scientific knowledge in areas such as renewable energy integration, carbon capture, and water recycling. Recognizing these needs, ALPHA collaborates with a diverse range of stakeholders, extending beyond its internal resources to achieve innovation breakthroughs.

> *"Some of the breakthroughs we've achieved in water conservation would not have been possible without the expertise of our academic partners who specialize in hydrochemistry." – Senior R&D manager at ALPHA*

External partners bring specialized expertise that accelerates the commercialization of innovations. For example, partnerships with competitors allow ALPHA to address cumulative environmental impacts and share infrastructure challenges, as in the making of heavy trucks.

> *"The mining industry increasingly works with NGOs and universities to conduct proper research. This allows us to understand complex problems comprehensively, something we can't achieve with internal resources alone." – Sustainability manager at ALPHA*

In project COL-012, ALPHA collaborated with CHI, a leading university, and ZETA, a competitor, to develop proprietary tailings management technology aimed at minimizing environmental risks from mining waste. This partnership accelerated innovation by leveraging external expertise and ensured advanced research translated into impactful applications.

> *"Academia brought the theoretical framework, while we provided the operational insights to make it work on the ground" - Project leader at ALPHA*

Risk sharing and financial efficiency. Collaborating with external stakeholders also enables ALPHA to share the financial burden and risks associated with developing sustainability-driven innovations. Given the capital-intensive nature of mining and the uncertainties surrounding new technologies, collaborations distribute costs and risks across multiple stakeholders, making high-risk projects more feasible.

> *"When we partner with others, the shared investment reduces the pressure on us to bear the entire financial risk. It also signals to stakeholders that we're committed to advancing industry-wide sustainability." - Sustainability officer at ALPHA*

Collaboration proves essential for large-scale initiatives with uncertain technological feasibility and market acceptance. In project COL-001, ALPHA partnered with BETA to develop low-emission smelting technology, sharing financial and technological resources to distribute upfront costs and achieve economies of scale. This approach reduced duplication, mitigated the risks of unproven technologies, and accelerated innovation cycles while enhancing market adoption.

> *"The biggest incentive for external collaboration is addressing cumulative impact, especially in regions with overlapping industry footprints. Companies can share resources and responsibilities to reduce environmental impact." – Executive at ALPHA*

Accelerated technological innovation. Collaborations with supply chain partners and research institutions have been pivotal in expediting the development and deployment of sustainability-driven innovations. For example, in project COL-007, ALPHA partnered with ZETA, a competitor, PHI and IOTA, two global equipment manufacturers, to design electric mining trucks tailored to ALPHA and ZETA operational needs. This collaboration not only

delivered a customized solution but also significantly reduced the time required to bring the trucks into production. These trucks are now operational, contributing to the firm's carbon reduction targets.

> *"We needed the trucks to meet very specific operational criteria, and working closely with the manufacturer allowed us to co-create a solution that aligned perfectly with our needs," - Manager at ALPHA.*

Joint ventures further enable ALPHA to scale technologies critical for decarbonization or energy transition goals. For instance, as part of project COL-001, ALPHA launched a joint-venture with BETA (a competitor) to create aluminum smelting technology that eliminates greenhouse gas emissions and produces oxygen as a by-product.

> *"Through initiatives like joint ventures, we can quickly adopt and scale new technologies that are not part of our core business but are critical for decarbonization or energy transition goals." – Sustainability manager at ALPHA*

Collaboration in sustainability-driven innovation presents strategic value but poses challenges for ALPHA, including IP disputes, misaligned priorities, and trust issues, which limit the effectiveness of collective efforts.

4.3.3. An array of challenges in collaborating with diverse stakeholders

Intellectual property disputes. Managing IP conflicts is a recurring challenge in university partnerships, rooted in the contrasting priorities of academic and corporate stakeholders. While collaborations with universities provide valuable contributions to sustainability-driven innovation, ALPHA often faces friction over IP ownership and licensing rights. The lack of standardized IP frameworks across institutions compels ALPHA to negotiate tailored agreements for each partnership, adding complexity to the collaboration process. Disputes frequently arise during early-stage research due to ambiguities around ownership, which intensify as projects evolve. For example, universities emphasize open-source knowledge dissemination to advance academic progress, whereas ALPHA prioritizes protecting proprietary data to maintain competitive advantages. These misaligned objectives

complicate negotiations, extend project timelines, and in some cases, deter otherwise promising partnerships.

> *"University collaborations are great, but negotiating IP rights is a big challenge. Universities often want to charge more for background IP after you've invested in developing the project, creating friction in the partnership." – R&D manager at ALPHA*

Collaboration challenges with competitors. Collaborating with competitors often creates tension over IP leakage and strategic misalignment. ALPHA remains cautious about sharing data and innovations, as the risk of competitive repercussions looms large. Balancing pre-competitive collaboration with competitive interests proves challenging, with companies hesitating to disclose critical information that could impact their strategic position.

> *"Navigating the balance between pre-competitive collaboration and competitive interests is tricky. Companies are often hesitant to fully reveal data due to regulatory or strategic concerns." – R&D engineer at ALPHA*

ALPHA encounters considerable difficulties in managing knowledge flows within its collaborative projects particularly with competitors. Sharing knowledge increases the risk of unintended information leaks and knowledge misappropriation. Differing strategic priorities and organizational cultures further complicate alignment and decision-making, creating friction that undermines trust and delays progress. These challenges are amplified in cutting-edge sustainability-driven innovation initiatives, where firms must delicately balance collaboration with preserving their competitive edge.

> *"A lot of companies do not share the entire knowledge or data that they have amongst each other. This lack of transparency and trust frequently hampers the innovation process, particularly when strategic objectives differ." Engineer at ALPHA*

Multi-stakeholder collaboration complexities. Collaborations with multiple stakeholders often encounter practical challenges, including legal complexities and budget misalignments. Collaborative projects frequently require extensive legal agreements, such as Non-Disclosure Agreements and privacy contracts, which can slow progress and delay

implementation. Differing budget priorities among partners further complicate alignment, potentially derailing projects before they even begin.

> *"Collaborations often get delayed due to misalignment of budgets or priorities between partners. This can cause entire projects to collapse before they even start." – Project leader at ALPHA*

ALPHA faces significant challenges in managing the legal and financial complexities of multi-stakeholder collaborations. Prolonged negotiations over resource allocation, budgets, and contractual terms often lead to delays and heightened tensions. Misaligned expectations around cost-sharing and revenue distribution further strain partnerships, particularly in large-scale sustainability-driven innovation projects where diverse stakeholder priorities and financial constraints complicate effective collaboration.

> *"Non-disclosure agreements and privacy contracts can delay progress for months, especially with multiple partners. It's like buying a house—if one link breaks, the entire chain collapses." – Manager at ALPHA*

Time pressures and mistrust. Collaborative efforts are further complicated by time pressures, particularly with the urgency of achieving net-zero goals. Rushed timelines often lead to stakeholder exclusion, eroding trust and creating political challenges.

> *"Time pressure can backfire in collaborations. Pushing for faster outcomes can lead to political challenges and stakeholders feeling excluded." – Manager at ALPHA*

Mistrust also poses significant barriers to impactful collaboration. Hesitation among firms to co-invest in large-scale projects limits their potential, as financial commitments are often viewed as high-risk.

> *"Investment in collaborative sustainability-driven innovation is often blocked by hesitation to co-invest. Companies prefer to collaborate up to a point but hesitate when substantial financial commitments are required." – Business development at ALPHA*

ALPHA faces notable challenges in multi-stakeholder collaborations for sustainability-driven innovation, including trust deficits from perceived imbalances, partner capacity limitations causing bottlenecks, and misaligned timelines and expectations that disrupt effectiveness.

5. Discussion

5.1. Implications for research

This study contributes to the literature on sustainability-driven innovation in resource-intensive industries by addressing gaps in understanding how firms can develop such innovation. Our findings illuminate how firms navigate these challenges by integrating internal control with external collaboration to achieve sustainability objectives.

First, this study brings valuable insights by showing the evolving set of determinants that influence sustainability-driven innovation. While regulatory mandates, stakeholder demands, and competitive pressures remain foundational (Porter & Van der Linde, 1995; Horbach, 2008), this research identifies additional determinants specific to resource-intensive industry, such as addressing cumulative environmental impacts and fostering regional collaboration in overlapping industrial areas. These new determinants are particularly critical as they reflect the systemic nature of sustainability challenges, where the environmental consequences of operations often extend beyond firm boundaries and require collective action. Addressing cumulative impacts necessitates holistic strategies that integrate multiple stakeholders, while regional collaboration ensures shared accountability and resource efficiency across interconnected industries. These findings align with Rennings (2000) on environmental innovation externalities and expand this understanding by emphasizing spatial and regional dimensions specific to resource-intensive sectors.

Second, our findings also reveal that balancing internal development and external inter-organizational collaboration is essential. This dual strategy reflects the increasing need for firms to integrate their internal capabilities with external expertise to tackle sustainability challenges that exceed the scope of any single organization (Parmigiani, 2007; Puranam et al., 2013). The interplay between these approaches demonstrates that internal and external projects are not alternatives but complementary pathways for achieving sustainability goals. Indeed,

internal projects enable firms to develop proprietary technologies tailored to their strategic needs, fostering innovation that can serve as a competitive differentiator. These internally driven initiatives enable firms to retain control over intellectual property, refine processes, and ensure that innovations are seamlessly integrated into their broader strategic frameworks. In contrast, external inter-organizational collaborations leverage the collective expertise and resources of diverse stakeholders, pooling capabilities that transcend the limitations of any single organization (Albort-Morant et al., 2018; Pagell & Wu, 2009). Such collaboration are particularly effective in addressing systemic challenges (Schot & Steinmueller, 2018) that require cross-industry coordination, shared investment, and the adoption of pre-competitive frameworks. The synergy between internal and external lies in their ability to mutually reinforce each other. Proprietary technologies developed through internal projects often serve as foundational innovations that can be scaled and adapted through collaborative efforts. For instance, internally developed low-carbon processing methods can be further refined and implemented across supply chains via partnerships with suppliers or competitors. Similarly, insights gained from external collaborations often inform the strategic direction and technical refinement of internal projects, creating a virtuous cycle of innovation (Watson et al., 2010; Ritala & Gustafsson, 2021).

Third, this study complements and extends existing literature by underscoring ALPHA's ability to balance internal and external innovation approaches, highlighting a nuanced form of organizational ambidexterity (O'Reilly & Tushman, 2013; Raisch & Birkinshaw, 2008). Internal innovation provides scalability, differentiation, and alignment with firm-specific objectives, as emphasized in studies on resource-based advantages (Barney, 1991; Wernerfelt, 1984). External inter-organizational collaborations, on the other hand, mitigate risks, shorten innovation cycles, and address systemic challenges that exceed the capacity of individual firms, resonating with recent findings on the importance of

interorganizational networks in sustainability (Ritala et al., 2014; Roh et al., 2023). These findings build on the exploration-exploitation framework in organizational learning (March, 1991), demonstrating how firms can simultaneously pursue efficiency and adaptability to navigate sustainability challenges. ALPHA's ability to integrate these strategies underscores the interplay between proprietary control and collaborative agility, highlighting how these dual pathways are interdependent rather than independent mechanisms for fostering sustainability-driven innovation. This contribution deepens the understanding of how firms navigate the complexities of sustainability-driven innovation, offering new insights into the strategic ambidexterity required to thrive in resource-intensive.

5.2. Implications for practice

The findings offer actionable insights for practitioners managing sustainability-driven innovation in high-impact industries. Internal projects, such as low-emission technology development, highlight the long-term benefits of proprietary innovation, including enhanced market positioning and reduced regulatory risks. Practitioners should prioritize investments in core technological capabilities that align with strategic goals and integrate deeply into value chains. Equally important is the role of partnerships in addressing systemic challenges. ALPHA's collaborations with competitors, suppliers, and academic institutions demonstrate the value of pooling resources and expertise to accelerate innovation cycles and share financial risks. Practitioners should adopt a portfolio approach (Chiambaretto & Fernandez, 2016), allocating projects based on complexity, regulatory needs, and stakeholder expectations. Furthermore, engaging stakeholders is critical. ALPHA's initiatives, such as incorporating local labor and co-developing solutions with indigenous communities, show how stakeholder-centric innovation can reduce risks and create shared value. Practitioners should embed stakeholder engagement into their innovation strategies to achieve both environmental and reputational gains.

5.3. Limitations and directions for future research

While this study provides valuable insights, it is not without limitations., Though ALPHA's status as a global mining leader provides a compelling basis for analysis, the single case study design limits generalizability. Future research should explore multiple firms and sectors to identify broader trends and differences. Quantitative studies could complement our qualitative approach by assessing the relative impacts of internal and collaborative strategies on sustainability outcomes. Additionally, this research focuses primarily on the corporate level but overlook broader organizational influences on the diverse embedded innovation projects such as leadership commitment and cultural dynamics. Future studies could examine how structures and practices shape the effectiveness of sustainability-driven innovation. Finally, the governance mechanisms that underpin successful partnerships warrant further investigation. While ALPHA's collaborative projects highlight co-created value, they also expose challenges in aligning stakeholder interests (Gnyawali & Park, 2011; Ritala et al., 2014). Future research could explore how firms structure partnerships to balance cooperation and competition (Fernandez et al., 2014, 2018), ensuring mutual benefits while safeguarding proprietary interests. These areas of inquiry can deepen understanding of sustainability-driven innovation in resource-intensive industries.

6. Concluding remarks

This research uncovers how firms in resource-intensive industries can effectively integrate internal and external strategies to advance sustainability-driven innovation. By exploring ALPHA's practices, we highlight the importance of balancing internal projects with external inter-organizational collaboration to address sustainability-driven innovation challenges. This study provides a foundation for both scholars and practitioners to explore innovative pathways for achieving sustainability in complex, high-impact industries.

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TABLE 1 – OVERVIEW OF THE DIFFERENCE OF TERMS USED

Type of Innovation Terms used	Definition	Primary Focus	Scope of Impact	Distinctive Characteristics	References
Eco-Innovation	Development or modification of products, processes, services, or models to reduce environmental impact throughout their lifecycle.	Reduction of environmental risks and resource depletion.	Product, process, organizational practices	Lifecycle approach to mitigate ecological risks, minimizes waste and emissions, boosts environmental and economic gains.	Kemp & Pearson (2007); Carrillo-Hermosilla et al. (2010); Horbach et al. (2012); Álvarez et al. (2014)
Green Innovation	Innovation in products and processes aimed at pollution prevention, waste reduction, and eco-efficiency within organizations.	Prevention of pollution and waste.	Primarily product- and process-level	Product-focused, with a narrower, environmental-only focus on pollution reduction and organizational eco-efficiency.	Kemp & Chen et al. (2006); Pontoglio (2007); Eiadat et al. (2008); Nidumolu et al. (2009); Schiederig et al. (2012)
Sustainable Innovation	Innovations designed to integrate social, economic, and environmental value creation, promoting triple bottom line outcomes.	Social, environmental , and economic benefits (triple bottom line).	Broad, extending beyond environment to social areas	Broadens scope to include societal and economic impact, embedding sustainability into organizational core values and strategies.	Elkington (1997); Lüdeke-Freund (2010); Szekely & Strebel (2013); Bocken et al. (2014); Adams et al. (2016)
Environmental Innovation	Innovations aimed exclusively at enhancing ecological outcomes, typically through reduced resource consumption and pollutive emissions across the lifecycle of the activity.	Strictly ecological benefits.	Environmental performance	Narrow focus on reducing ecological footprint without necessarily considering economic or social gains; aligns with strict ecological performance.	Rennings (2000); Rehfeld et al. (2007); Huber (2008); Ekins (2010); Ghisetti & Pontoni (2015)

TABLE 2 – LIST OF PRIMARY AND SECONDARY DATA

Data Type	Source	Description	Volume	Purpose
Primary Data	30 Semi-structured Interviews	Interviews with executives, R&D experts, and project managers focusing on corporate strategies and project-level sustainability-driven innovations.	450 pages	To capture strategic and operational insights into internal and collaborative sustainability-driven innovation strategies.
	Video Conferencing (Recorded/Noted)	Conducted over video calls; audio-recorded where possible and transcribed; detailed notes were taken when recording was not feasible.	~60 minutes each	To ensure in-depth, multi-level data collection for a comprehensive understanding of innovation dynamics.
Secondary Data	Industry Reports	Reports from ICMM, government bodies, and NGOs on global trends, technologies, and regulations affecting the mining industry.	500 pages	To contextualize industry-specific sustainability challenges and emerging technologies.
	Corporate Sustainability Reports	ALPHA's internal reports detailing decarbonization, resource efficiency, and circular economy initiatives.	Detailed sections	To validate claims and provide insight into specific projects and commitments.
	Media Coverage & Third-Party Evaluations	Press releases and external evaluations on ALPHA's stakeholder collaborations and industry reputation.	Various	To verify collaboration outcomes and stakeholder engagement in eco-innovation initiatives.
Triangulation	Cross-referencing Primary and Secondary Sources	Ensured consistency between interview data, internal documents, and external reports to identify and address discrepancies.	Iterative process	To enhance the validity and reliability of findings, ensuring a holistic understanding of innovation strategies.

FIGURE 1 – DATA CODING

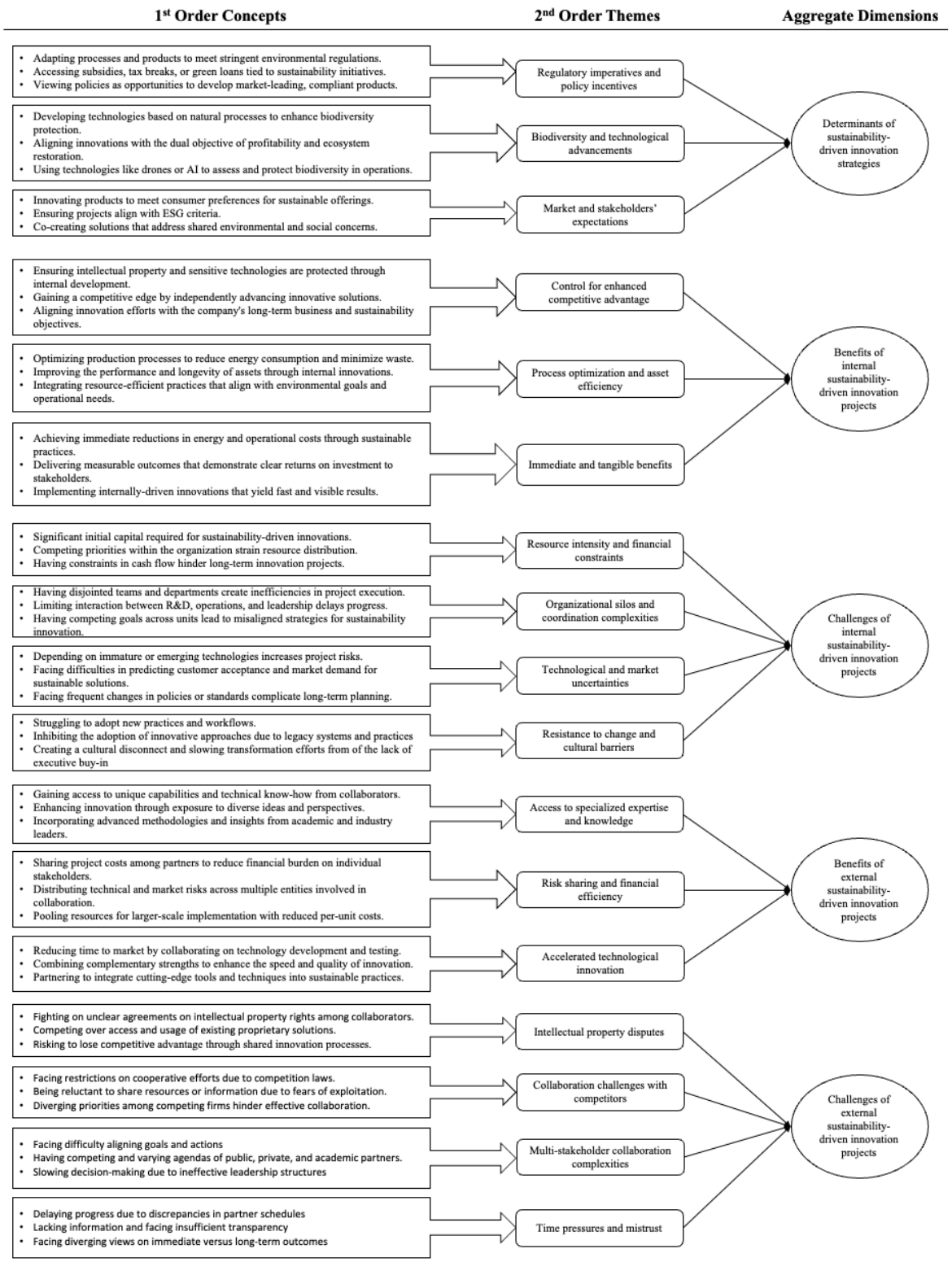

TABLE 3 – LIST OF ALPHA'S INTERNAL SUSTAINABILITY-DRIVEN INNOVATION PROJECTS

Date	Initiative Code	Type	Objective	Outcome
2020	**INT-001**	Internal Investment	Invest in emission reduction initiatives targeting significant decreases in absolute and intensity metrics.	Achieving alignment with global climate goals and initiated long-term decarbonization efforts.
2020	**INT-002**	Research & Development	Develop renewable energy and storage systems to transition mining operations away from fossil fuels.	Reducing reliance on fossil fuels and enhanced energy resilience in operations.
2021	**INT-003**	Research & Development	Develop low-carbon industrial processes to achieve significant emissions reductions.	Launching pilot programs to test scalable, innovative solutions.
2023	**INT-004**	Pilot Project	Explore biofuel feedstock as an alternative to traditional diesel to decrease emissions.	Advancing biofuel initiatives and strengthened domestic fuel security efforts.
2023	**INT-005**	Long-Term Agreement	Secure long-term renewable energy supply for industrial operations to reduce operational emissions.	Ensuring sustainable operation with reduced carbon footprint and supported local communities.
2024	**INT-006**	Strategic Acquisition	Expand capabilities in critical mineral production to support electrification and sustainability goals.	Enhancing capacity in materials essential for the green energy transition.
2024	**INT-007**	Venture Investment	Back innovative technology startups focused on sustainable resource extraction methods.	Initiating pilot projects to validate low-cost, sustainable extraction processes.

TABLE 4 – LIST OF ALPHA'S SUSTAINABILITY-DRIVEN INNOVATION COLLABORATIVE PROJECTS

Date	Initiative Code	Type	Participants	Objective	Outcome
2020	**COL-001**	Joint-Venture	Company ALPHA Company BETA, Company GAMMA, Government OMEGA	Develop technology that eliminates greenhouse gas emissions in industrial processes.	Deploying zero-emission technology at a pilot facility, advancing sustainable production.
2020	**COL-002**	Partnership	Company ALPHA, Company DELTA	Explore and implement low-carbon solutions across the supply chain to reduce emissions.	Decarbonizing the supply chain, focusing on low-carbon pathways.
2021	**COL-003**	Partnership	Company ALPHA, Company EPSILON	Develop digital platforms and technologies to support circular and sustainable ecosystems.	Evaluating innovative solutions including microgrids and AI for decarbonization.
2021	**COL-004**	Global Competition	Company ALPHA, Company ZETA, Company PSI Organization UPSILON	Develop concepts for large-scale equipment electrification systems to reduce emissions.	Selecting innovators to progress with solutions for electrification in operations.
2022	**COL-005**	Partnership	Company ALPHA, Company ETA	Supply responsibly sourced materials for sustainable vehicle production.	Advancing commitments in supply chains, contributing to decarbonized transportation solutions.
2023	**COL-006**	Memorandum of Understanding	Company ALPHA, Company THETA	Collaborate on low-carbon technologies for industrial processes, including renewable inputs.	Exploring low-carbon solutions, emphasizing high-quality raw materials.
2023	**COL-007**	Partnership	Company ALPHA, Company ZETA, Company PHI, Company IOTA	Test zero-emission machinery to reduce operational greenhouse gas emissions.	Conducting trials to assess productivity of zero-emission machinery in operations.
2024	**COL-008**	Venture Investment	Company ALPHA, Startup SIGMA	Develop filtration technology for resource extraction without water or chemicals.	Planning pilot plant to demonstrate cost-efficient and sustainable extraction methods.
2024	**COL-009**	Partnership	Company ALPHA, Company KAPPA	Develop a large-scale resource project to support critical mineral supply.	Attracting substantial investment for project development, aiming for significant capacity.
2024	**COL-010**	Partnership	Company ALPHA, Company LAMBDA	Supply responsibly sourced materials for sustainable manufacturing.	Reducing emissions by up to 70% through low-carbon material integration.
2024	**COL-011**	Partnership	Company ALPHA, Company OMICRON	Boost regional supply of critical resources for renewable energy applications.	Targeting production capacity to meet significant demand for renewable energy infrastructure.
2024	**COL-012**	Global Competition	Company ALPHA, Company ZETA, University CHI	Innovate in tailings management to enhance sustainability.	Piloting methods for safer tailings disposal and global standards improvement.