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SUSTAINABLE OPEN INNOVATION INTERACTIONS IN INDUSTRIAL SECTOR PARTNERSHIPS*
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Abstract. The adoption of open innovation (OI) practices emerges as a key catalyst for sustainable innovation, generating multiple organizational advantages in industrial sectors. This study examines how OI outcomes derive from the configurational effects of interconnected OI interactions. Through fuzzy-set qualitative comparative analysis (fsQCA) examining 48 European innovation partnerships in industrial sectors, the research identifies two distinct configurational pathways to achieve elevated sustainable innovation output: the Broad approach and Platform-targeted approach. Conversely, two configurations result in low innovation output: the Isolated and Platform-missing approaches. The study establishes that platform and complex systems engagement represents a fundamental condition for high sustainable OI output - though insufficient in isolation, the results suggest its robust connection with sustainable open innovation. The findings establish that OI outcomes depend on interaction configuration effects and present a framework for analyzing pathways to enhance OI effectiveness in industrial sectors. Additionally, the paper provides managerial guidance for optimizing sustainable innovation outputs based on distinct OI interaction strategies.

Keywords: green technology adoption; fuzzy-set qualitative comparative analysis; sustainable open innovation; innovation outcomes; industrial sectors

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1. Introduction

The transition towards sustainable industrial practices is a pressing challenge in the face of accelerating climate change and environmental degradation. The adoption of open innovation (OI) practices is argued to be a driving force of green/sustainable innovation, providing multiple organizational advantages (McGahan et al., 2021), but also enabling industries to develop eco-friendly technologies, reduce carbon footprints, and enhance circular economy practices (Urbinati et al., 2023). Organizations can enhance their sustainability practices and innovation processes through OI implementation, enabling them to maintain competitive advantage and technological currency (Obradovic et al., 2021). Though concepts linking openness with sustainability have emerged recently, such as "sustainable open innovation" (Bigliardi et al., 2020; Bogers et al., 2020), Kimpimäki et al. (2022) note that thorough investigation of this research domain remains limited. This study addresses this gap by exploring the role of OI interaction pathways in climate-resilient industrial practices. Organizations can pursue global sustainability objectives while maintaining market competitiveness by implementing OI within

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environmental contexts. This makes the topic particularly relevant for both organizational leadership and policy stakeholders across industrial sectors.

OI interactions consist of inbound, outbound, and coupled processes that reflect diverse organizational functions and relationships (Bogers et al., 2017; Audretsch & Belitski, 2023). They manifest through various channels including academia-industry collaborations, user innovation, crowdsourcing, licensing, and open data utilization (Beck et al., 2022). Throughout this paper, the term "interaction channels" is used to refer to the specific mechanisms through which organizations engage in OI activities. These channels serve as conduits for knowledge flow and collaborative innovation efforts between an organization and its external environment. Configurations, in contrast, refer to the particular combinations of these interaction channels that organizations implement in their OI strategies. These interaction channels (in different configurations) aim to create an environment conducive to innovation success. Platform-based systems, crowdsourcing communities, and open data represent key constructs for network-level research (Bogers et al., 2017), with channel selection contingent on industry specifications and needs. The decision to choose particular channels is influenced also by partnership characteristics and stakeholder preferences. These interaction channels facilitate sustainable business models and technological advancement, enabling organizations to maintain competitiveness (Obradovic et al., 2021). The OI - sustainability relationship is complex and multifaceted, spanning multiple industries and research domains. While interaction channels for promoting sustainability may vary, evidence indicates that OI practices effectively drive sustainable innovation and environmental solutions (Milana & Ulrich, 2022).

Current OI research emphasizes sustainability, although studies primarily examine individual interaction channels' effects on organizational performance (Ogink et al., 2023). This singular focus fails to capture the complex interplay of factors influencing environment-related innovation. Regional variations in OI implementation, sustainability development, and resource distribution require an understanding of how multiple interaction channels collectively shape innovation outcomes to develop effective, sustainable innovation strategies. Simple cause-effect analysis proves insufficient for comprehending the mechanisms driving sustainable OI results. While previous studies have acknowledged the importance of various interaction channels in OI, there is a lack of comprehensive analysis on how different configurations of these channels impact green innovation outcomes. Understanding how these configurations affect the degree of innovation—incremental versus radical—could yield insights into optimizing collaboration strategies for enhanced sustainable innovation outputs.

Furthermore, research has indicated that the connection between green process innovation and effectiveness may be non-linear, yet this aspect has not been thoroughly investigated within the context of OI. Specifically, how varying levels of engagement in OI influence the outcomes associated with sustainable innovations remains unclear. This gap suggests a need for studies that explore potential tipping points or thresholds in OI engagement that lead to significant improvements in sustainable innovation performance. Considering the above, this study investigates the following research question: How do different configurations of open innovation interaction channels influence sustainable innovation output in industrial partnerships?

Through this paper, we develop a framework for configuring OI interactions leading to high (and non-high) green OI output, which facilitates an understanding of the systemic dynamics and multifaceted structure of OI efforts toward green innovation. This research, therefore, contributes to the ongoing discourse on sustainable innovation by highlighting the role of OI in enhancing environmental performance. Given the urgency of climate mitigation and adaptation efforts, understanding the optimal pathways for sustainable open innovation is essential for policymakers, industry leaders, and research institutions working towards a low-carbon future.

2. Theoretical background

Open innovation has gained considerable attention in recent years as a catalyst of sustainable innovation. Bogers et al. (2017) expand on the traditional OI model by introducing the concept of Sustainable Open Innovation, which integrates sustainability objectives into the OI framework. This approach emphasizes that innovation efforts should not only focus on economic gains but also consider mental impacts. OI facilitates a dynamic

innovation process by breaking down organizational silos and fostering collective intelligence, allowing companies to accelerate growth and tackle complex challenges more effectively, facilitating collaboration that is essential for addressing environmental challenges. This decentralized approach to innovation is especially valuable for fostering green technologies and sustainable practices. The integration of OI into sustainable practices has been recognized as vital for organizations aiming to enhance their environmental performance. By leveraging external collaborations—such as partnerships with stakeholders, crowdsourcing, and co-creation—companies can develop innovative solutions that address sustainability issues more effectively (Strazzullo et al., 2025). In the green innovation context, ecosystems are therefore crucial for pooling diverse expertise and technologies to tackle multifaceted environmental issues.

In this paper, we build upon the research of McPhillips et al. (2024), which highlights the various interaction channels in OI, such as platforms, technology transfer, crowdsourcing, user engagement, and external knowledge sourcing, all of which play a pivotal role in advancing sustainability goals. These channels enable firms to leverage diverse sources of knowledge, increasing their capacity for green innovation. External knowledge sourcing is one of the most widely studied OI interaction channels. It involves collaborations between universities, industries, and other organizations to exchange knowledge and spur innovation (Radziwon & Bogers, 2019). These collaborations not only lead to the successful development of sustainable products but also create opportunities for dealing with global challenges, including energy constraints. External knowledge sharing is critical in industries with fast-paced innovation cycles, as it allows firms to stay competitive while contributing to sustainable development. Platforms have become essential for firms engaging in OI, offering a structured means to integrate external knowledge and foster collaboration. These digital ecosystems facilitate the co-creation of innovation by connecting diverse stakeholders, including users, developers, and external organizations, allowing them to share knowledge and resources more efficiently (Cenamor & Fris-Hammar, 2021). Platforms offer modularity and interoperability, enabling organizations to scale their innovation efforts while maintaining control over intellectual property (Gawer & Cusumano, 2014). This modular approach is especially beneficial for sustainability initiatives, where innovation often requires collaboration across sectors to address environmental challenges. Digital platforms enable firms to build and manage collaborative networks that can accelerate the development of environmentally friendly products and processes (Obradovic et al., 2021). These platforms often incorporate features such as open data sharing, which supports sustainable innovation by giving access to valuable environmental information that can be used in the design of greener technologies (Bertello et al., 2024). Additionally, platform-based systems can support sustainability by facilitating the integration of circular economy practices, enabling firms to develop innovations that minimize waste and promote resource efficiency (Urbinati et al., 2023).

Technology transfer is another key OI interaction channel that accelerates the development of sustainable innovations. Gawer & Cusumano (2014) discuss the role of technology transfer in enabling firms to access and apply cutting-edge technologies, which is particularly important for sustainability-oriented projects. However, challenges such as intellectual property concerns and knowledge leakages often hinder technology transfer efforts. Despite these obstacles, technology transfer remains crucial for sustainable innovation, as it helps organizations capitalize on new technologies while maintaining their competitive advantage (Fernandes et al., 2021). Crowdsourcing, another significant OI channel, taps into the collective intelligence of a broad audience to generate ideas and solutions. This approach is especially valuable for sustainable innovation, allowing firms to gather diverse perspectives on environmental challenges. Literature highlights the role of crowdsourcing in generating funding for environmentally sustainable projects (Testa et al., 2023). The integration of crowdsourcing in OI partnerships facilitates the development of more inclusive and impactful sustainable innovations.

Overall, the literature supports the idea that different OI interaction channels play a crucial role in driving sustainable innovation. However, the effectiveness of these channels depends on the collaboration mechanisms in place, including cross-sector partnerships and stakeholder engagement (McPhillips et al., 2024). The complexity of managing diverse stakeholder expectations and the risks associated with intellectual property remain significant challenges. Nonetheless, orchestrating OI interaction could provide a strategic framework for organizations aiming to integrate sustainability into their innovation processes and address pressing global environmental issues. On the other side, some researchers explore the "dark side" of openness (Dahlander et al.,

2021), discussing how excessive openness can lead to issues such as knowledge leakage and loss of control over innovation processes. This perspective provides an interesting lens through which to view our fsQCA results, particularly the absence of certain OI practices in some sufficient configurations. It suggests that organizations may need to adopt a selective approach to OI, carefully balancing the benefits of external collaboration with the need to protect core competencies and intellectual property.

In the context of OI targeting sustainable solutions, Resource-Based View (RBV) framework highlights the significance of strategically managing valuable, inimitable, and non-substitutable resources (Barney et al., 2010; Marzi et al., 2023). OI interactions serve as valuable resources by creating synergies that enable firms to innovate and respond to environmental challenges effectively. However, their true potential is realized when combined with inimitable resources, such as organizational culture, specialized knowledge, or unique stakeholder relationships. The non-substitutability of these assets ensures that firms can maintain their competitive edge even as market conditions evolve. This study integrates RBV into the analysis of OI interactions, exploring how the interplay of these resource gateways contributes to achieving high (or low) levels of green innovation output.

Research on innovation interactions, particularly in the context of OI and green solutions, has traditionally relied on linear models and regression analyses. However, the fsQCA methodology offers a robust alternative that is particularly suited for addressing the complexities inherent in these interactions. FsQCA is designed to handle causal complexity by recognizing that multiple conditions can lead to the same outcome (equifinality). This means that different combinations of factors can result in similar levels of innovation output, making it ideal for studying OI interactions where various elements contribute to success. This is particularly relevant in green solutions, where diverse technological, organizational, and environmental factors interplay. By integrating qualitative insights with quantitative rigour, fsQCA enables a nuanced analysis that captures both the richness of qualitative data and the systematic nature of quantitative methods. This duality facilitates a deeper exploration of how specific conditions combine to foster innovation (Pappas et al., 2021).

3. Methodology and research design

3.1 FsQCA analysis

To address the research question of evaluating different configurations of the influence of OI interaction channels on sustainable innovation output, we employ fuzzy-set qualitative comparative analysis (fsQCA) to examine 48 European industrial partnerships. FsQCA is a confirmatory method using set theory and fuzzy algebra (Ragin, 2008). The method presumes that causal variables (conditions) function interdependently, allowing for the identification of diverse yet equally valid routes to achieve identical outcomes (Fiss, 2011; Douglas et al., 2020; Pappas et al., 2021). Through case comparison, researchers can identify logical relationships between variable patterns and results (Rihoux & Lobe, 2009). Using fsQCA 3.0 software to analyze multiple conditions' synergy involves three phases. Phase one is variable calibration: Assigning set membership to cases. Phase two is a necessity analysis: using Boolean algebra for consistency and coverage calculations. Consistency shows the importance and determines configuration consideration. Coverage indicates configuration significance (Ragin, 2008). Conditions with consistency ≥ 0.9 are necessary.

The consistency formula is (Eq.1):

$$Consistency(X_i \geq Y_i) = \frac{\sum [\min(X_i, Y_i)]}{\sum (Y_i)} \quad (Eq.1)$$

The coverage formula is (Eq.2):

$$Coverage(X_i \geq Y_i) = \frac{\sum [\min(X_i, Y_i)]}{\sum (X_i)} \quad (Eq.2):$$

Where X_i is the calibrated antecedent condition, Y_i is the calibrated result condition for unit i .

The third phase is a sufficiency analysis; it reveals sufficient condition combinations for results. First, truth tables show if cases with specific condition combinations lead to the same outcomes (Hartmann et al., 2022). Truth tables display all logical configurations between causal conditions. Second, tables are reduced using frequency threshold (in our study 2) (Schneider & Wagemann, 2012) and consistency threshold (in our study 0.8). Finally, Boolean minimization and Quine-McCluskey algorithm determine configurations. Consistency and coverage indices for adequacy analysis are defined as follows (Eq.3 and Eq.4):

$$\text{Consistency}(X_i \leq Y_i) = \frac{\sum [\min(X_i, Y_i)]}{\sum (X_i)}$$

$$\text{Coverage}(X_i \leq Y_i) = \frac{\sum [\min(X_i, Y_i)]}{\sum (Y_i)}$$

(Eq.3, Eq.4)

Where X_i is the calibrated antecedent condition, Y_i is the calibrated result for unit i .

3.2 Sample

The fsQCA analysis was applied to European OI partnerships in industrial sectors to uncover the OI interaction channel combinations that lead to high (or low) innovation outputs regarding sustainable solutions. We employed a multi-stage sampling strategy to ensure a robust and representative sample of European OI partnerships. We first identified a preliminary pool of 110 partnerships from publicly available databases (e.g., EU-funded project directories, industry association listings, and national R&D registers). These partnerships were screened based on the following criteria: (a) multi-partner, R&D-oriented collaborations; (b) involvement of at least one research institution; (c) establishment beyond the initial formation stage, ensuring at least one year of collaborative activity; and (d) a stated objective focusing on green or sustainable innovation. Applying these criteria yielded 48 qualified cases. Our sample meets the recommended minimum ratio of 2 cases per condition for 6 conditions (Marx, 2010). While a larger sample would be ideal, our current sample size is sufficient for exploratory fsQCA analysis. To ensure data quality and reliability, we collected information through multiple sources: questionnaires, semi-structured interviews with partnership coordinators, internal project documents (e.g., meeting notes, technical reports), public deliverables, patent databases, and government R&D records. This mixed-method approach enabled triangulation, reducing the risk of measurement error and increasing confidence in our dataset.

The analysis was based on a model that considered six potential conditions representing interaction channels in an OI partnership (McPhillips et al., 2024): sourcing external knowledge (ExterKnowl), technology transfer (TechTrans), platforms and complex systems (PlatfAndComplSys), user-driven activity (UserDriv), crowdsourcing (Crowdsour) and utilizing Open data (OpenData). Only interaction channels that demonstrated theoretical connection with existing literature, as explored in empirical OI studies and confirmed by the initial background, were included in this analysis. Each construct was defined and aggregated, based on the foundation of extant literature on OI partnerships.

Given the requirement of an outcome measure for fsQCA, our research aimed to evaluate the impact of the six interaction channels as conditions for the success of OI output. We adopted the definition of innovation output (Bacon & Williams, 2022), which refers to "active interaction between organizations, leading to measurable and effective application by the recipient organization." Such an approach enables us to compare diverse cases across industrial sectors and geographical locations in OI collaboration, focusing on innovation performance (Audretsch & Belitski, 2023). In our article, we focus primarily on OI processes with a higher level of impact on the innovation output, dealing with complex, multi-sided problems that require the integration of diverse knowledge domains (Ooms & Piepenbrink, 2021). Such processes facilitate radical innovation and are not limited to the bounds of an individual partner, making OI essential in addressing these challenges. In contrast, we define not-high innovation output as incremental innovation, which is typically constricted by the product's structure (e.g., modularity) and does not involve revolutionary solutions. To distinguish "high innovation output" from "not-high innovation output," we established data-driven thresholds: cases in the top quartile of

the composite innovation score were coded as high, while those in the bottom half were coded as not-high. The fsQCA allowed us to compare and contrast these outcome sets. The reported solution coverage and consistency measures (e.g., coverage exceeding 0.85 and consistency often above 0.80 in complex solutions) reinforce that the outcome calibration effectively discriminates between higher and lower-performing OI collaborations.

Each OI interaction condition—Sourcing of External Knowledge, Technology Transfer, Platforms and Complex Systems, User-Driven Activity, Crowdsourcing, and Open Data—was operationalized with reference to validated scales from prior open innovation research. We developed a structured questionnaire with Likert items, where higher scores signified greater intensity of involvement in the respective OI activities. Before fielding the questionnaire, a pilot study was conducted with five industry managers and two academic experts to refine item wording and ensure conceptual clarity. We evaluated scale reliability using Cronbach's alpha and found values above 0.70 for all constructs, indicating acceptable internal consistency. Confirmatory factor analysis further supported the discriminant and convergent validity of the operationalization. These steps ensured that the conditions used in fsQCA were grounded in sound measurement principles. Descriptive statistics were used to indicate that the six conditions in the model vary across cases, with ExterKnowl having the highest mean and Crowdsour having the highest standard deviation. The results, therefore, highlight the variability of the conditions across cases. An assessment of individual condition necessity was performed prior to analyzing their influence on outcomes, demonstrating the complexity of the OI process.

This study employed direct calibration to translate the Likert-scale measures into membership values that span from 0, indicating complete non-membership, to 1, representing full membership in the set. Drawing on established guidelines (Fiss, 2011) and expert feedback from the pilot phase, we set the full membership at the upper end of the observed distribution (approximately the 95th percentile), the set's full non-membership threshold near the lower end (approximately the 5th percentile), and a cross-over point (0.5) reflecting the qualitative midpoint. We performed sensitivity checks by slightly adjusting these calibration thresholds to verify that the solution patterns remained stable. The high consistency and coverage values for both high and not-high innovation output solutions indicated that these calibration decisions were robust. For instance, the identified parsimonious and complex solutions consistently demonstrated solution coverage above 0.77 and solution consistency values around or above 0.75, confirming the reliability of the chosen calibration benchmarks.

Following calibration, we constructed truth tables by listing all configurations of the six OI interaction conditions and assigning cases to each configuration according to their fuzzy-set memberships. We applied a frequency threshold of two cases per configuration to ensure that the patterns identified were empirically grounded. Consistency thresholds were selected to strike a balance between stringent selection of configurations and retaining meaningful patterns. The reported solutions—both complex and parsimonious—exhibited high coverage and acceptable consistency values, indicating that the identified causal configurations reliably explain the presence or absence of high innovation output. Robustness checks, including adjusting calibration thresholds and removing borderline cases, confirmed that the identified core conditions remained stable. This internal consistency across analytic variations bolsters the credibility of our findings.

4. Results

The conditional configuration results reveal paths explaining both high and low OI output levels, with each column representing a possible configuration. For high OI output, the four configuration conditions show 0.939 solution consistency, meaning 93.9% of cases meeting these configurations demonstrate high OI output levels. The solution coverage of 0.779 indicates these configurations explain 77.9% of high OI cases. Similarly, for low OI output level configurations, solution consistency is 0.963, with solution coverage of 0.824. Both solutions' consistency and coverage exceed critical threshold, confirming the empirical analysis's validity.

Table 1. Configuration result of OI output levels

Conditions	High level of OI output				Low level of OI output			
	H1	H2	H3	H4	L1	L2	L3	L4
ExterKnowl	•	•	•	Ø	•	•	Ø	•
TechTrans	•		Ø	Ø	Ø	Ø	•	•
PlatfAndComplSys	•	•	•	•		Ø	Ø	Ø
UserDriv	•	•	Ø	Ø	Ø			Ø
Crowdsour		•	Ø	Ø	Ø	Ø	Ø	Ø
OpenData	Ø	•	Ø	•	Ø	Ø	Ø	•
consistency	0.928	0.932	0.966	0.907	0.948	0.929	0.966	0.998
raw coverage	0.432	0.346	0.197	0.245	0.567	0.412	0.331	0.268
unique coverage	0.174	0.138	0.038	0.147	0.048	0.097	0.065	0.095
solution coverage	0.779				0.824			
solution consistency	0.939				0.963			

In data tables: "•" shows condition is present; "Ø" shows condition is absent; blank spaces indicate "do not care" conditions (irrelevant to outcome).

We categorized the four high-level OI output paths into two categories (Table 1):

- Broad approach to OI interactions (paths H1 and H2) indicates engagement in multiple OI interaction channels, which may be particularly important for high technology and science-based sectors that greatly rely on such input. Therefore, OI-implementing companies in these sectors should formulate approaches that capitalize on the exchange of knowledge, encompassing both the inflow and outflow of insights within these knowledge-rich ecosystems.
- Platform targeted approach (paths H3 and H4) encompasses two variations that similarly result in high levels of innovation output. These two share the condition connected to using platforms and complex systems and only differ in the presence of one other channel of OI interaction (sourcing of external knowledge or utilizing open data). The proposed solutions imply that, in many cases, it's important to organize OI efforts around using platforms and complex systems, but it may be beneficial to limit the engagement in many other interactions and thus optimize resource and time allocation.

We categorized the four low-level OI output paths into two categories (Table 1):

- Isolated approach (paths L1, L2, L3) indicates engagement in only one of OI interaction channels, which seems not enough to yield high OI output.
- Platform missing approach (path L4) makes it apparent that engaging in multiple OI interaction channels but without including the platforms and complex systems may result in low level of OI outputs.

5. Discussion

Our fsQCA findings highlight that multiple configurations of OI interaction conditions can lead to similar outcomes (causal asymmetry). The nuanced configurations reflected in the complex, intermediate, and parsimonious solutions demonstrate that no single OI practice is universally effective—rather, effectiveness depends on a tailored combination of conditions. For example, the presence of Platforms and Complex Systems emerged repeatedly as a central condition in configurations tied to high innovation output, showing strong coverage and consistency in the identified solutions. In contrast, the absence of platforms and certain OI activities characterized not-high innovation output solutions. For instance, "Platform-Missing" pathways demonstrate that interaction channels such as external knowledge sourcing and user-driven innovation often fail to achieve synergy without a centralized coordinating mechanism. The findings suggest that the inefficacy of such pathways lies in fragmented resource utilization and insufficient collaboration. Organizations can address these shortcomings by adopting modular platform designs that allow gradual integration of interaction channels, ultimately transitioning toward higher output configurations. In an expanding trend, numerous industries are structuring their operations around core platforms, which are further accompanied and complemented by networks or constellations of partner organizations. In the present-day landscape, the influence of digital transformation has further intensified the adoption of platform-centric approaches (Bogers et al., 2017). Hence, platformization emerges as a crucial facilitator for OI by simplifying the onboarding and collaboration of diverse

new participants. It also seems to serve as a pertinent variable influencing the efficiency of OI toward green solutions.

Additional sources used for the triangulation of the research show that in the studied cases, platforms seem to act as hubs that centralize diverse interaction channels: enable organizations to source and share knowledge efficiently across boundaries, leveraging external expertise; facilitate the collection and integration of ideas from external contributors like customers, researchers, or the public; offer structured mechanisms for capturing user feedback and co-creating solutions. This centralized integration reduces inefficiencies and creates synergies between interaction channels, amplifying their collective impact on innovation. Moreover, platforms inherently foster scalability through network effects: as more users and partners engage, the value of the platform grows exponentially, leading to richer interactions and more robust innovation ecosystems. For example, a platform connecting multiple organizations can exponentially increase the diversity of knowledge inputs, which is an important driver of radical innovation. Platforms also enable seamless coordination among multiple stakeholders: streamline the management of complex, multi-partner projects by offering shared tools and workflows, optimize resource distribution, ensuring that inputs like data, funding, and expertise are directed where they are most needed, act as orchestrators, aligning the goals of various participants and fostering collaboration. This capability is especially critical in large-scale partnerships involving diverse sectors, as seen in green innovation efforts. Platforms are often digital, leveraging advanced technologies like data analytics and artificial intelligence to: extract actionable insights from large datasets, facilitate real-time decision-making based on user behavior, market trends, and environmental conditions. Platforms often reduce costs and simplify access to shared resources, including intellectual property, technical expertise, and funding opportunities. Empirical evidence from fsQCA analysis serves as the backbone of high-performing innovation systems, not only enhancing the effectiveness of existing innovation efforts but also unlocking new possibilities for radically sustainable solutions. Their role in green innovation is particularly pronounced, as they bridge the gaps between diverse stakeholders and ensure efficient use of resources. The study analysis underlines their necessity but also their insufficiency when isolated. Moreover, while platforms are presented as critical enablers of green innovation, there are potential challenges, such as high costs of implementation, dependency risks, and privacy concerns. SMEs, for instance, may face barriers to adopting platforms due to limited financial and technical resources. Future research should explore modular platform designs or shared ecosystems to reduce costs and encourage broader participation. Governance frameworks to ensure data security and equitable access could further mitigate risks.

The rest of the conditions, namely sourcing of external knowledge (ExterKnowl), engaging in technology transfer (TechTrans), user-driven activity (UserDriv), utilizing open data (OpenData) and crowdsourcing (Crowdsour), are of a much less significance and in some cases engagement in those interaction channels without utilizing platforms and complex systems (PlatfAndComplSys) might lead to lower levels of innovation output. These findings are noteworthy as they underscore the significance of strategizing the OI effort. They reveal that, even at elevated levels of a specific channel of OI interaction, low innovation outputs can be obtained when crucial conditions are lacking (Marzi et al., 2023). It has to be noted, however, that despite evidence of the contribution of singular OI interaction channels to OI performance, decision-makers often underestimate the share of each contribution as a source of innovation and that error can have severe consequences for firms' competitiveness and innovation policies.

These results indicate that the configurations of OI interaction channels can differ in their capacity to efficiently and effectively coordinate resources within specific OI partnerships. Embracing the somewhat risky adoption of OI interaction pathways compels organizations to make present commitments and resource allocations, even when the outcomes may be realized in the long term (Bigliardi et al., 2020). Organizations engaging in OI partnerships must remember that utilizing an effective interaction channel is not enough. Seizing the effect of organizational learning on innovative behaviour typically involves the combined evaluation of different factors that include the support of managers and boundary-spanning leadership, employee training, promoting experimentation, fostering risk-taking, and cultivating an attitude that values self-efficacy (Obradovic et al., 2021; Ogink et al., 2023).

This study draws on RBV to explore how organizations combine and utilize interaction channels as competitive resources to drive green innovation. When applied to sustainable OI, RBV highlights that interaction channels like platforms, external knowledge sourcing, and user-driven activities serve as strategic resources that enhance an organization's innovation capabilities. These channels enable access to diverse know-how bases, cutting-edge technologies, and collaborative possibilities that would otherwise remain inaccessible. By strategically configuring these resources, firms can optimize their innovation outputs and align them with sustainability goals (Marzi et al., 2023). The findings underscore the importance of RBV's dimensions in driving high levels of green innovation output, ultimately contributing to both academic literature and practical strategies for sustainable OI. Platforms and complex systems emerged as central elements in successful configurations, serving as valuable resources facilitating knowledge exchange and co-creation among stakeholders. Non-substitutability was evident in cases where alternative resources failed to match the functionality or impact of the existing configurations, reinforcing the necessity of strategically managing unique assets within OI ecosystems.

From a method perspective, while some configurations show low unique coverage, they still contribute to explaining the outcome in combination with other conditions. For instance, configuration H3 has a unique coverage of 0.038, indicating that while it explains a small portion of the outcome by itself, it's part of a larger explanatory model when combined with other configurations. By reporting the specific coverage and consistency values associated with each configuration, we underscore the reliability and explanatory power of these patterns. Recent studies confirm that there are multiple configurations or "causal recipes" that facilitate high levels of green innovation. Our fsQCA analysis identifies combinations like high external knowledge sourcing, platform use, and user engagement as significant drivers. This reflects findings in sustainability research, highlighting that firms often combine different strategies based on their specific resources and market conditions to achieve green innovation (Borah et al., 2023).

Conclusions

This study set out to explore how different OI interaction configurations shape sustainable innovation outcomes. By applying fsQCA, we identified multiple pathways leading to both high and low innovation outputs, addressing our research question: "How do different configurations of open innovation interaction channels influence sustainable innovation output in industrial partnerships?" The findings underline that the role of using platforms and complex systems holds specific significance as it is a common factor in both types of engagement, leading to high OI output. Even though this OI interaction channel is not sufficient to on its own generate high OI output for green solutions, the results suggest a more robust connection with green open OI than what previous empirical work had presumed.

Organizations implementing OI maintain competitive advantages over those using closed innovation systems. Research and practice demonstrate OI's positive contribution to sustainability outcomes, though establishing and leveraging various interaction channels remains challenging. The sustainability context introduces additional complexities to OI processes, with each partnership developing distinct pathways toward sustainability goals (Bogers et al., 2020; McGahan et al., 2021). By examining the interplay between OI and sustainability-focused innovation, this research extends existing models and introduces a novel approach designed to analyze pathways for enhancing the effectiveness of OI. First, our study emphasizes the configurational effects of OI interactions. Utilizing the fsQCA method, we identify specific conditions under which OI interactions lead to high versus low innovation outputs. This approach is significant as it moves beyond linear models, highlighting the importance of complex condition configurations in achieving successful innovation outcomes (Radziwon & Bogers, 2019; Ogink et al., 2023). Such an analysis not only demonstrates the multifaceted nature of OI but also addresses the issue of causal asymmetry, where different configurations can lead to similar outcomes, underscoring the non-linear relationships that typify OI interactions.

Moreover, the framework proposed in this study deepens the systematic understanding of OI-driven pathways by showing how certain configurations of conditions facilitate the effectiveness of green innovation strategies. This introduces a fresh perspective to OI effectiveness research, as limited knowledge exists regarding the factors contributing to low levels of innovation output amidst extensive OI engagement (Marzi et al., 2023).

This is particularly important as it provides actionable insights for managers and policymakers looking to optimize OI processes under varying conditions. Managers should prioritize the adoption and integration of platforms that facilitate collaboration across diverse stakeholders. These platforms enable resource pooling, knowledge sharing, and modular innovation, which are essential for tackling complex environmental challenges. The findings highlight that isolated engagement in a single OI interaction channel, or a lack of platform-based collaboration, is insufficient for generating high innovation outputs. Managers should avoid relying exclusively on singular approaches, such as technology transfer or crowdsourcing, and instead adopt a more integrative strategy that combines multiple complementary channels. This study also suggests creating transitional pathways that allow organizations to move from low to high output configurations. Strategies could include phased investments in platform infrastructure, targeted training for stakeholders, or pilot programs to test new interaction channels.

Our findings underline the pivotal role of digital technologies and platforms in shaping OI strategies. Emerging technologies, including artificial intelligence and blockchain, hold transformative potential for enhancing platform capabilities in green innovation. AI-powered platforms can optimize the allocation of resources in real-time, enabling organizations to reduce waste and increase efficiency. Blockchain, on the other hand, ensures transparency and accountability, particularly in sustainable supply chains. For example, platforms leveraging these technologies can facilitate circular economy practices by tracking materials through their lifecycle and enabling their reuse or recycling. Integrating these advancements into platform ecosystems will further strengthen their role in achieving green goals. By analyzing how digital tools facilitate or hinder sustainable OI practices, these findings contribute to the evolving discourse on the digital transformation of both innovation and sustainability processes (Cenamor & Fris-Hammar, 2021).

Platforms can also serve as critical enablers for policy frameworks promoting sustainability. By fostering transparency and traceability, platforms can help organizations monitor compliance with environmental regulations and incentivize sustainable practices. For example, blockchain-enabled platforms can track carbon footprints across supply chains, ensuring adherence to global climate goals. Policies that support platform adoption, such as subsidies for digital infrastructure or mandates for open data sharing, can amplify these benefits, making platforms integral to achieving national and international sustainability targets. SMEs often face challenges in accessing and utilizing platforms. Policymakers could develop programs to reduce these barriers, such as subsidized platform access, technical training, and the creation of shared innovation infrastructures tailored to SMEs and resource-constrained organizations.

In terms of limitations, the study analyzes industrial sectors. A multi-sectoral breakdown would allow researchers to identify best practices and challenges specific to each context. Tailored recommendations for sectors could maximize the applicability of findings and inform more precise strategies for achieving high innovation outputs in green innovation efforts. Similarly, while this study touches on the concept of ecosystems, a deeper integration of ecosystem theory could enrich the analysis. Ecosystem theory provides a lens to understand how platforms orchestrate diverse interaction channels, enabling synergies across organizational boundaries. Embedding these frameworks into future studies would deepen theoretical insights and strengthen the foundation for understanding the role of platforms in sustainable innovation.

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