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Technopreneurial opportunities in the green hydrogen economy: A framework for green-tech venture creation with gender-based insights

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ABSTRACT

This study examines how technopreneurial opportunities influence green-tech venture creation in Malaysia's emerging green hydrogen economy, with a specific focus on identifying gender disparities and the mediating role of Sustainable Market Readiness (SMR). Integrating the Resource-Based View, Institutional Theory, and a Gendered Ecosystem Perspective, the research evaluates how capabilities and structural constraints shape entrepreneurial outcomes across genders. Utilizing survey data from 431 Malaysian entrepreneurs, Structural Equation Modelling (SEM) and multi-group analysis were applied. The findings indicate that technopreneurial opportunities significantly drive venture creation, with SMR acting as a vital complementary mediating mechanism. However, multi-group analysis reveals distinct structural disparities: male technopreneurs exhibit stronger effects in converting recognized opportunities and market conditions into actual business ventures. Conversely, female technopreneurs face persistent systemic challenges—such as limited access to finance and restricted entry into formal industry networks—that dampen the impact of their entrepreneurial efforts. Addressing these disparities is critical, as diverse participation enhances innovation capacity and supports more inclusive and sustainable transitions. The study advances theoretical integration and highlights the need for gender-sensitive strategies in Malaysia's green hydrogen ecosystem.

1. Introduction

The global pursuit of carbon neutrality has accelerated clean energy innovation, positioning green hydrogen as a pivotal solution to address the climate crisis (Evro et al., 2024). Produced through the electrolysis of water using renewable energy, green hydrogen offers a clean and versatile energy carrier capable of decarbonizing key sectors such as manufacturing, transportation, and power generation (Hassan, Jalil, et al., 2024; Kazi et al., 2021; Li et al., Sun, & Song, 2023). As countries intensify efforts to meet climate targets, green hydrogen has become a strategic priority, with projections suggesting it could contribute up to 12% of global energy use by 2050 (Boretti & Pollet, 2024; Hassan, Nassar, et al., 2024). This transition creates significant opportunities for technopreneurship, where innovation, digital integration, and sustainable business models drive the development of solutions across the hydrogen value chain, including production, storage, distribution, and utilization (Abdin, 2024; Baquero & Monsalve, 2024). However, despite

this potential, participation remains uneven, particularly for women, whose engagement in the green hydrogen economy is constrained by structural and technical barriers, including limited representation in engineering and energy-related fields in Malaysia. Without targeted efforts to enhance inclusivity, the benefits of this emerging sector risk being inequitably distributed, limiting both innovation capacity and the broader impact of sustainable energy transitions.

The importance of green-tech venture creation lies in its ability to bridge the gap between technology development and real-world application (Jorzik et al., 2024). While research institutions and governments often spearhead the technological aspects of green hydrogen (Islam et al., 2024), the commercialization, scaling, and localization of these innovations depend heavily on entrepreneurial actors (Schwabe, 2024). In the context of this study, green-tech venture creation refers to the process by which technopreneurs establish and grow businesses that design, commercialize, and implement innovative solutions across the green hydrogen value chain—from production and storage to

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distribution and end-use applications. These ventures not only introduce new technologies but also adapt them to local market needs, regulatory frameworks, and sustainability goals. Green-tech ventures act as vital engines for economic growth, job creation, and climate resilience (Hu et al., 2024). By converting scientific knowledge into marketable solutions, they accelerate the adoption of green hydrogen while addressing regional challenges such as energy access, industrial emissions, and waste management (Kleimann et al., 2023).

Since green hydrogen gains traction, there is a critical need to ensure that the technopreneurial opportunities it creates are inclusive and equitable. A growing body of research (such as Nguyen et al., 2023; Chen et al., 2023; Fertő & Bojnec, 2025), suggests that gender disparities in entrepreneurship and innovation persist across sectors, including the green economy. Women remain underrepresented in science, technology, engineering, and mathematics (STEM) fields (Nash & Moore, 2024), are less likely to secure venture capital and institutional funding (Van den Heuvel & Popp, 2023), and often lack access to networks, mentorship, and policy support (Turley et al., 2025). These structural inequalities constrain women's participation in high-potential areas such as green-tech venture creation, particularly in frontier sectors like green hydrogen.

In the context of technopreneurship where innovation, risk-taking, and technology-driven enterprise converge, these gender-based barriers can significantly limit the diversity and inclusivity of entrepreneurial ecosystems (Kovaleva et al., 2023). For women, especially in developing nations, the path to green-tech venture creation is frequently hindered by limited market access, sociocultural expectations, and institutional blind spots (Fallah & Soori, 2023; Jiang et al., 2024). In Malaysia, these challenges are further intensified by restricted access to formal financing channels, underrepresentation in industry decision-making networks, and limited inclusion in large-scale energy projects and public-private partnerships, which are critical entry points into the green hydrogen sector. Without targeted intervention, these disparities risk excluding a significant portion of the population from the benefits of green hydrogen commercialization, and more broadly, from contributing to the global sustainability agenda (Athia et al., 2024). In the context of green hydrogen, which is still in its formative stages, these disparities threaten to exclude women from shaping and benefiting from one of Malaysia's most forward-looking industries.

Despite a growing focus on entrepreneurship and innovation, gender disparities in Malaysia's technopreneurial ecosystem remain evident. In Malaysia, the green hydrogen economy is becoming increasingly relevant as the nation strives to align its development agenda with global sustainability commitments (Jumaat & Khalid, 2024). This includes adherence to the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), particularly SDG 5 (Gender Equality) and SDG 13 (Climate Action). The Twelfth Malaysia Plan (2021–2025) and the National Energy Transition Roadmap outline ambitious strategies to achieve net-zero emissions by 2050 (Zhong et al., 2025), with green hydrogen identified as a critical enabler of future energy resilience and environmental stewardship (Abdin, 2024). Regions such as Sarawak have already taken significant steps by investing in green hydrogen infrastructure and pilot projects, positioning themselves as pioneers in Southeast Asia's hydrogen ecosystem (Zakaria et al., 2023). Sarawak, rich in hydropower resources, has emerged as a national leader in green hydrogen development (Rahman & Wahid, 2021). The state launched Southeast Asia's first integrated hydrogen production plant and refueling station, and its public buses powered by hydrogen are already in operation. Such developments demonstrate the technical feasibility and policy interest in scaling hydrogen infrastructure, while also signalling the potential for public-private partnerships to drive green-tech innovation.

Despite its potential, technopreneurship in the green hydrogen sector faces several challenges. High capital requirements, long development timelines, and complex regulatory environments present substantial barriers to entry (Bade et al., 2024; Nurdawati & Urban, 2022).

Malaysia's hydrogen ecosystem remains in its nascent stages, and much of the technology is imported (Ahmad et al., 2021). This opens a window of opportunity for local technopreneurs and SMEs to step in and offer indigenous solutions that are cost-effective, adaptable, and aligned with local needs. However, gaps in entrepreneurial capacity, limited funding channels, insufficient R&D collaboration, and a lack of clear regulatory frameworks remain key barriers (Ohene et al., 2023; Torres de Oliveira et al., 2022). Additionally, the market is often uncertain due to lack of demand aggregation (Weissenburger et al., 2024), pricing mechanisms (Wang et al., 2022), and standardized safety protocols (Genovese et al., 2023). These conditions disproportionately affect small-scale technopreneurs and underrepresented groups, such as women and youth, who may lack the financial resilience or institutional connections to navigate these obstacles.

Moreover, the entrepreneurial support system—comprising incubators, accelerators, research institutions, and venture capital networks—often lacks specific programs for hydrogen-focused ventures. In Malaysia, while agency like Malaysian Global Innovation and Creativity Center (MaGIC) support tech-based entrepreneurship (Felker, 2025), their alignment with hydrogen innovation remains limited. This ecosystem misalignment restricts the translation of policy ambition into real entrepreneurial outcomes and reduces the scalability of green hydrogen innovations.

To address these challenges, this article proposes that Sustainable Market Readiness (SMR) serves as a critical mediating factor that can enable or inhibit the translation of technopreneurial potential into actual green-tech venture creation—particularly for women. SMR refers to the degree to which the surrounding ecosystem is prepared to support green innovation (Schrank & Kijkasiwat, 2024). In the context of this study, SMR is conceptualized as the readiness of Malaysia's entrepreneurial ecosystem to integrate gender inclusivity into its green hydrogen agenda, ensuring that technopreneurs have equitable opportunities to participate in and benefit from emerging markets. It highlights not only the availability of supportive infrastructure and policies but also the extent to which these supports are accessible and inclusive, thereby determining whether innovative ideas in the green hydrogen sector can be transformed into viable and sustainable business ventures.

By acting as a mediator, SMR can shape how gender disparities influence entrepreneurial engagement. In environments with high market readiness, women technopreneurs are more likely to access necessary resources (Fallah & Soori, 2023), scale their innovations, and gain market entry (Khodor et al., 2024). Conversely, in markets where readiness is low, even highly capable and motivated women may be deterred or excluded from participating in green-tech ventures (Rajak & Dolan, 2024). Thus, the mediating effect of SMR is not just instrumental—it is transformative, with the potential to level the playing field and foster a more inclusive innovation ecosystem.

Crucially, the SMR of Malaysia's entrepreneurial ecosystem—reflected in its policies, infrastructure, and institutional support—plays a mediating role in determining whether technopreneurial opportunities are accessible and actionable. Without addressing these readiness factors through a gender-responsive lens, Malaysia risks limiting the full potential of its green hydrogen sector by excluding a significant portion of its innovation talent from the green-tech economy. Policies that enhance market readiness—such as gender-sensitive procurement, targeted funding schemes, inclusive innovation hubs, and equitable STEM education—can mitigate structural barriers and create a pathway for inclusive green hydrogen entrepreneurship (Gatto, 2022; Sakib et al., 2024).

Although gender disparities in entrepreneurship are widely acknowledged, evidence from Malaysia highlights the severity of the gap in technology-intensive sectors such as green hydrogen. Only 20.6% of formal business owners in Malaysia are women (Tirumalaisamy et al., 2024), and less than 10% are engaged in STEM-related enterprises (Murdiati et al., 2023). Koch et al. (2025) noted that women entrepreneurs receive disproportionately lower access to government funding

and venture capital, with fewer than 5% of technology-based SME grants awarded to women-owned firms. Structural barriers continue to constrain women's entry into high-growth green-tech industries. This underrepresentation limits women's ability to fully engage in critical areas such as hydrogen production, storage, distribution, and application across industries. Moreover, policy frameworks and market structures in the green hydrogen sector tend to overlook gender-sensitive considerations, reinforcing barriers to women's entry and growth in this domain. Despite Malaysia's push toward green hydrogen as part of its net-zero agenda, these disparities raise concerns about inclusivity in one of the fastest-growing clean energy markets, as the exclusion of women risks narrowing the innovation base, slowing knowledge transfer, and undermining the broader societal acceptance of green hydrogen solutions. Therefore, the study proposed the following research questions (RQs).

- **RQ1:** *What is the influence of technopreneurial opportunities within the green hydrogen economy on green-tech venture creation in Malaysia?*
- **RQ2:** *How does sustainable market readiness mediate the relationship between technopreneurial opportunities and green-tech venture creation in Malaysia's green hydrogen economy?*
- **RQ3:** *What are the differences between male and female technopreneurs in accessing and leveraging technopreneurial opportunities for green-tech venture creation in Malaysia's green hydrogen sector?*

This study holds both theoretical and practical significance as it advances a multidimensional understanding of how gender disparities influence technopreneurial participation and green-tech venture creation within Malaysia's emerging green hydrogen economy. Theoretically, the research integrates the Resource-Based View (RBV), Institutional Theory, and the Gendered Ecosystem Perspective to form a novel framework that examines how access to resources, institutional readiness, and ecosystem dynamics shape entrepreneurial outcomes across genders. By applying the RBV, the study underscores technopreneurial opportunities—such as technopreneurial orientation, opportunity recognition, and resource mobilization—as critical strategic possessions that can lead to competitive advantage in the high-potential, green-tech space. However, the realization of these opportunities is not uniform across demographic groups. The incorporation of Institutional Theory enables the study to capture the mediating role of SMR, which includes the availability of enabling infrastructure, regulatory frameworks, and supportive policies necessary to facilitate the commercialization of green hydrogen technologies. Importantly, this study deepens the theoretical lens by applying the Gendered Ecosystem Perspective, which exposes how gendered norms, institutional biases, and unequal access to support systems result in structural disadvantages for women technopreneurs. In doing so, it fills a critical research gap in green entrepreneurship and energy transition literature by not only identifying barriers but also assessing the systemic enablers that could mitigate gender disparities. Practically, the findings will offer actionable insights for Malaysian policymakers, innovation agencies, and green economy stakeholders to design more inclusive and gender-responsive policies, programs, and financing instruments. The study also informs capacity-building strategies for women-led green-tech ventures, ensuring that Malaysia's green hydrogen transition is not only technologically viable and economically sound but also socially equitable and inclusive of all innovation contributors.

The remainder of this paper is structured as follows. Section 2 reviews the existing literature and establishes the integrated theoretical framework combining the Resource-Based View, Institutional Theory, and the Gendered Ecosystem Perspective, culminating in the development of the study's core hypotheses. Section 3 outlines the quantitative methodology, detailing the questionnaire design, translation protocols, stratified random sampling framework, and the structural equation modelling (SEM) approach. Section 4 presents the empirical results, including assessments of measurement validity, structural path

relationships, mediation mechanisms, and multi-group invariance analyses across genders. Section 5 synthesizes these findings within a broader discussion on inclusive green technopreneurship. Finally, Section 6 concludes the paper by summarizing the theoretical and practical implications, acknowledging study limitations, and offering strategic directions for future research.

2. Literature review and hypothesis development

2.1. Theoretical perspective

The Resource-Based View (RBV) posits that a firm's or entrepreneur's ability to achieve competitive advantage and long-term sustainability is contingent upon access to valuable, rare, inimitable, and non-substitutable resources (Clulow et al., 2003). In the context of technopreneurship within the green hydrogen economy, resources such as technological know-how (Alkaraan et al., 2024), innovation capabilities (Khanra et al., 2022), access to green financing (Llach et al., 2025), and renewable energy infrastructure (Tran et al., 2020) are critical enablers of green-tech venture creation. Technopreneurial opportunities—defined as access to these innovation-based resources—are thus foundational to new venture development (Kahpi et al., 2024). However, disparities in how these opportunities are distributed and accessed can result in uneven entrepreneurial outcomes. Prior studies suggest that women entrepreneurs often have less access to financial capital (Khabbaz & Kuran, 2024), strategic networks (Kakeesh, 2024), and specialized knowledge (Zahra, 2021), which may inhibit their ability to identify or exploit green technology-related opportunities (Chaudhuri et al., 2023). In the Malaysian context, this disparity is particularly relevant given the nascent stage of the green hydrogen sector and the predominance of male-led participation in STEM-based ventures. Therefore, RBV provides a foundational lens to assess how technopreneurial opportunities—particularly in high-tech green sectors—are linked to venture creation outcomes and how these relationships may be influenced by gender.

While RBV focuses on internal resource endowments, Institutional Theory provides a complementary perspective by examining the external environment that shapes entrepreneurial behaviour (Welter & Smallbone, 2011). Institutional Theory argues that formal institutions (e.g., regulatory frameworks, government policies) and informal institutions (e.g., cultural norms, social expectations) collectively influence individual and organizational action (Zenger et al., 2000). In green entrepreneurship, and particularly in sectors such as green hydrogen (Gasbarro et al., 2018), policy frameworks (Zhao, Liu, & Shu, 2021), market incentives (Nikolaou et al., 2018), access to certification mechanisms (Girma et al., 2025), and infrastructure investment (Inderberg et al., 2023) are critical external factors that either enable or constrain venture creation. This study conceptualizes SMR as an institutional construct that captures the readiness of the ecosystem to support green-tech ventures. SMR includes elements such as the maturity of the regulatory environment (Demir et al., 2023), availability of technical support and green financing (Safi et al., 2024), infrastructure adequacy (Adjei-Bamfo et al., 2019), and alignment of public-private collaboration (Casady et al., 2024). For technopreneurs, particularly women, the presence—or absence—of these institutional supports can significantly affect their capacity to act on entrepreneurial opportunities. Thus, Institutional Theory supports the investigation of SMR as a mediating variable that bridges technopreneurial opportunities and green-tech venture creation.

The Gendered Ecosystem Perspective extends beyond the traditional entrepreneurship and innovation literature by highlighting how entrepreneurial ecosystems are not neutral, but are often implicitly structured in ways that benefit men over women (Brush et al., 2019). This perspective emphasizes that gender disparities are not solely the result of individual limitations, but are deeply embedded in the design and functioning of the broader entrepreneurial ecosystem. Women

entrepreneurs frequently encounter structural barriers such as gender bias in investor decision-making (Leitch et al., 2018), male-dominated networks (Socratous, 2018), gender-neutral policies that fail to address differentiated needs (García & Welter, 2013), and a lack of role models in technology-intensive sectors (Mari et al., 2024). In Malaysia, although policies exist to encourage women's participation in entrepreneurship (Au et al., 2021), there is limited focus on facilitating their engagement in high-growth, innovation-based sectors such as renewable energy or green hydrogen. The gendered ecosystem lens is therefore essential for uncovering how technopreneurial opportunities are differentially experienced by men and women, and for analysing how institutional readiness (SMR) may either reinforce or mitigate these disparities. It provides a necessary analytical tool to interpret why, even when opportunities and resources are technically available, women may be less likely to convert them into successful ventures.

Together, the integration of RBV, Institutional Theory, and the Gendered Ecosystem Perspective enables a comprehensive exploration of the complex dynamics involved in gender disparities in green-tech entrepreneurship. RBV anchors the importance of resource access (technopreneurial opportunities), Institutional Theory contextualizes how ecosystem readiness mediates entrepreneurial outcomes (SMR), and the Gendered Ecosystem Perspective reveals how systemic inequities influence the distribution and activation of these resources. Unlike prior studies that often examine these theories in isolation within entrepreneurship, gender studies, or clean energy transitions, this study advances the literature by weaving them together to explain gender-specific pathways in the emerging and underexplored green hydrogen economy. While alternative frameworks such as Social Capital Theory or Human Capital Theory could offer insights into networks or skills, they fall short of capturing the institutional and structural inequities that uniquely shape gendered participation in green-tech sectors. Similarly, Transition Theories on sustainability provide a macro-level lens but overlook the micro-level entrepreneurial dynamics central to this study. By contrast, RBV, Institutional Theory, and the Gendered Ecosystem Perspective together provide a multi-layered rationale—linking resource mobilization, institutional readiness, and systemic inequities—that is particularly suited to unpacking gendered disparities in Malaysia's green hydrogen economy.

This paper specifically contributes to the literature by establishing a novel, cross-level conceptual model that shifts the gender-gap discourse from individual capability deficits to deeply embedded ecosystem limitations within frontier clean energy markets. By uncovering how SMR functions as a transformative institutional pipeline, the study maps the exact operational paths through which structural disadvantages—such as restricted entry to elite public-private networks and capital allocation biases—interfere with a female technopreneur's capacity to exploit viable opportunities. This integrative approach highlights how gendered constraints intersect with institutional readiness and resource mobilization, producing differentiated entrepreneurial outcomes that have not been sufficiently theorized in clean energy contexts. Ultimately, this study fills a critical gap in green entrepreneurship literature by proving empirically that market readiness is not demographic-neutral; rather, it acts as a systemic filter that inadvertently favours male-centric industrial networks, thereby narrowing the clean-tech innovation base. Through this integration, the study moves beyond generic explanations of gender inequality and introduces a novel framework for understanding how structural, institutional, and resource-based factors interact to shape green-tech venture creation in Malaysia's green hydrogen sector. It also supports the formulation of policies that are not only economically strategic but also socially inclusive—ensuring that Malaysia's clean energy transition capitalizes on the full potential of its entrepreneurial base.

2.2. Technopreneurial opportunities in the green hydrogen economy

The global shift toward a low-carbon future has propelled green

hydrogen to the forefront of energy innovation, positioning it as a critical enabler in achieving net-zero emissions targets (Sebbagh et al., 2024). As a clean energy vector produced using renewable electricity through water electrolysis, green hydrogen offers substantial potential across diverse applications—from industrial decarbonization and long-duration energy storage to clean mobility and green manufacturing (Hassan, Viktor, et al., 2024). This transition has catalysed a surge in innovation and investment, opening new avenues for technopreneurs—entrepreneurs who leverage technology to create transformative, market-driven solutions in emerging industries. Within the green hydrogen economy, technopreneurs play a pivotal role in developing disruptive solutions for hydrogen production, storage, distribution, utilization, and digital integration (Baquero & Monsalve, 2024; Sharma et al., 2023). These developments not only generate economic value but also align with global sustainability goals, fostering an innovation landscape where environmental and entrepreneurial objectives converge.

Technopreneurship is increasingly recognized as a key driver of innovation-led growth in green technology sectors (Kahpi et al., 2024). In the context of green hydrogen, technopreneurs are uniquely positioned to address technological gaps, improve efficiency, and localize solutions tailored to specific market and environmental conditions (Caiafa et al., 2025). They contribute by developing compact and cost-effective electrolyzers, integrating hydrogen into fuel cell systems, and utilizing artificial intelligence (AI) and Internet of Things (IoT) for hydrogen infrastructure monitoring. The green hydrogen sector is particularly ripe for technopreneurial intervention due to its high innovation intensity and market nascency (Islam et al., 2024). Unlike mature renewable technologies such as solar and wind, green hydrogen remains underdeveloped, with significant room for new entrants to shape the technological landscape (Hassan, Nassar, et al., 2024). This openness creates unique opportunities for start-ups and independent technopreneurs to disrupt traditional energy paradigms and build scalable ventures.

Globally, countries like Germany, Japan, South Korea, and Australia have positioned green hydrogen as a strategic priority, creating funding schemes, partnerships, and innovation clusters that foster technopreneurship (Quitow et al., 2024). In these contexts, national roadmaps and public-private collaborations provide fertile ground for venture creation. Malaysia is also moving in this direction through the Hydrogen Economy and Technology Roadmap (HETR) and its aspirations to become a key exporter and domestic user of hydrogen (Zakaria et al., 2023). These developments suggest an emerging innovation ecosystem with potential for technopreneurial participation, particularly in renewable-powered hydrogen production, transport applications, and cross-border energy trade.

However, while national strategies signal institutional commitment, actual technopreneurial engagement remains constrained by several factors—including low awareness, limited access to green financing, and underdeveloped support infrastructure (Rathnayake & Roca, 2022). As a result, much of the innovation in Malaysia's green hydrogen economy is still dominated by large public or private players, limiting entry points for smaller ventures and individual innovators (Jumaat & Khalid, 2024). This highlights the need for ecosystem-level changes to support inclusive technopreneurial development. These opportunities, however, are influenced by several interconnected factors that shape the capacity of technopreneurs to recognize, act on, and scale their innovations. Among these, technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, and the entrepreneurial ecosystem are particularly significant.

2.3. Technopreneurial orientation and technopreneurial opportunities

Technopreneurial orientation refers to the strategic posture and mindset of individuals or firms toward innovation, risk-taking, and proactiveness in technological domains (Baysak et al., 2023; Maziriri

et al., 2025). In the context of the green hydrogen economy, TO is not simply a general entrepreneurial mindset but a capability to navigate uncertainty in rapidly evolving clean energy markets (Sunny & Shu, 2019). Entrepreneurs with strong technopreneurial orientation are more likely to pursue opportunities in cutting-edge sectors such as hydrogen fuel cells (Baquero & Monsalve, 2024), electrolyser design (Tebibel, 2021), and hydrogen-based energy storage systems (Inderberg et al., 2023). They also demonstrate the foresight to identify nascent niches like hydrogen-powered logistics, localized industrial decarbonization, and renewable-based hydrogen integration for off-grid communities (Dash et al., 2023). In Malaysia, national policies such as the HETR have begun to stimulate such orientations by signalling institutional support for hydrogen innovation (Jumaat & Khalid, 2024). However, the uptake remains uneven, particularly among women technopreneurs and SMEs, due to limited technical exposure and ecosystem gaps in hydrogen-related entrepreneurial training.

In high-tech and sustainability-driven sectors, TO becomes a decisive factor in whether entrepreneurs interpret systemic uncertainty as risk or as opportunity (St-Pierre et al., 2023). The green hydrogen economy—marked by regulatory fluidity, infrastructure bottlenecks, and market ambiguity (He et al., 2024; Shen et al., 2025)—provides a unique testing ground. Within this landscape, TO is hypothesized to be a critical antecedent to the recognition of high-potential yet highly uncertain technopreneurial opportunities.

Empirical research suggests that TO enhances cognitive alertness, market foresight, and the ability to process weak signals of change. For instance, Hällerstrand et al. (2023) found that proactive, innovative entrepreneurs in environmental sectors consistently identified sustainability opportunities earlier than incumbents. Applied to the green hydrogen sector, this implies that technopreneurs with strong orientation traits are more likely to detect opportunities arising from fragmented policies, pilot projects, and shifting industrial demand—areas where uncertainty discourages less forward-looking actors.

Specific to hydrogen innovation, technopreneurs with a high degree of orientation are more likely to experiment with pre-commercial technologies such as smart hydrogen microgrids, digital monitoring platforms for hydrogen distribution, and hybrid renewable-hydrogen systems (Baquero & Monsalve, 2024; Philip et al., 2022). This highlights that TO functions not only as a personality trait but as a strategic resource that allows entrepreneurs to transform institutional and technological uncertainty into actionable opportunities. In emerging economies like Malaysia, where hydrogen ecosystems are still nascent, such orientation provides first-mover advantages in setting industry norms, shaping policy dialogues, and capturing unstructured markets. Therefore, we propose the following hypothesis:

H1. *Technopreneurial orientation is positively associated with technopreneurial opportunities in the green hydrogen economy.*

2.4. Opportunity recognition and technopreneurial opportunities

Opportunity recognition—the ability to identify market gaps and innovation possibilities—is a central element of entrepreneurial success (Baron, 2006; Martínez-Cañas et al., 2023). In emerging sectors like green hydrogen, where technological and market uncertainties are high, the ability to perceive viable opportunities becomes a distinctive advantage. In this context, technopreneurs must identify how hydrogen-based solutions can mitigate global challenges such as carbon emissions, energy insecurity, and industrial pollution while also addressing localized needs (Vallejos-Romero et al., 2022). Examples include hydrogen-powered transportation, hydrogen blending in natural gas pipelines, and hydrogen use in carbon-intensive industries such as steel and cement—underexplored avenues in Southeast Asia with strong entrepreneurial potential. In Malaysia, while large energy firms are investing in hydrogen projects, SMEs and individual technopreneurs often lack the technical foresight and structured market intelligence to

identify these opportunities (Rahman & Wahid, 2021). Gender also plays a role: studies indicate that women entrepreneurs are frequently excluded from strategic networks where critical market insights circulate, leading to under-recognition of hydrogen business opportunities among female technopreneurs (Akhtar et al., 2023; Bentsen et al., 2023; Buchner et al., 2025).

Empirical evidence positions opportunity recognition as a precursor to entrepreneurial behavior and venture initiation, particularly in uncertain or dynamic sectors. Studies in technology-intensive and sustainability-oriented fields (Emami et al., 2023; Lanivich et al., 2024) highlight that individuals with heightened alertness and prior knowledge are more likely to perceive viable opportunities in nascent or underdeveloped markets. In renewable energy, entrepreneurs who recognize gaps in energy access, regulatory incentives, or environmental challenges are better positioned to deploy technological solutions that meet these needs (Falcone, 2023; Udemba et al., 2022). Within the green hydrogen economy, this process involves identifying emerging demands in transportation, power generation, and industrial decarbonization, while also detecting inefficiencies that innovative technologies could resolve. For example, technopreneurs alert to market shifts may pursue niches in electrolyser efficiency, hydrogen storage optimization, or digital certification and trading platforms. Studies by Kahpi et al. (2024) and Ba Awain et al. (2025) suggest that such recognition is often shaped by a blend of prior experience, environmental values, and responsiveness to regulatory or technological change.

In emerging markets like Malaysia—where the green hydrogen sector is still in its formative stage—opportunity recognition is especially critical for early-stage entrepreneurs. Research in Southeast Asia (Nepal et al., 2021; Thawesaengskulthai et al., 2024) confirms that early green ventures typically originate from actors capable of spotting unique openings in policy signals, resource endowments, and technology gaps. Therefore, we hypothesize:

H2. *Opportunity recognition is positively associated with technopreneurial opportunities in the green hydrogen economy.*

2.5. Resource mobilization and technopreneurial opportunities

Resource mobilization—the process of acquiring and combining financial, technological, human, and informational resources (Karami et al., 2024; Villanueva et al., 2012)—is a vital determinant of whether technopreneurial opportunities can be transformed into viable ventures. In the green hydrogen sector, this involves accessing R&D facilities, forming partnerships with research institutions (Lee & Kim, 2021), securing early-stage funding (Harichandan & Kar, 2023), and developing operational infrastructure such as production units, storage systems, and safety mechanisms (Walker & Klagge, 2024). Given the capital intensity and technical sophistication of hydrogen technologies, mobilizing resources is not only a practical challenge but also a strategic capability that differentiates successful ventures from stalled initiatives.

While agencies such as MaGIC and MTDC support Bumiputera and tech-based entrepreneurs in Malaysia (Ishak et al., 2025), hydrogen-specific resources remain concentrated among established incumbents, leaving SMEs and women-led ventures at the margins of this transition. Research consistently shows that the ability to mobilize resources determines whether recognized opportunities can be acted upon, especially in emerging industries. Parthiban et al. (2024) and Negri et al. (2025) found that entrepreneurs with strong opportunity recognition still fail to innovate if they lack access to resources. For technopreneurs in the green hydrogen economy, this challenge is amplified by high upfront costs and the need for advanced technical expertise across production, storage, distribution, and utilization systems (Müller & Eichhammer, 2023).

Resource mobilization extends beyond private capital to include institutional mechanisms—such as government grants, public-private partnerships, and university research collaborations—which are

particularly critical in hydrogen innovation due to its dependence on ecosystem coordination. For instance, Pierrakis et al. (2024) showed that clean-tech entrepreneurs leveraging R&D support from academic and government institutions were more likely to establish ventures in renewable energy. Similarly, Budumuru and Paruchuru (2025) found that non-traditional resourcefulness—such as repurposing existing infrastructure or tapping into digital networks—was often decisive for market entry in green innovation sectors. In Malaysia, entrepreneurs' capacity to engage in the hydrogen value chain is thus shaped not only by financial access but also by their ability to navigate institutional landscapes and forge strategic alliances (Ali et al., 2024).

This perspective suggests that resource mobilization in the green hydrogen economy is not merely about assembling inputs, but about creatively orchestrating financial, technical, and institutional assets under conditions of high uncertainty. In doing so, technopreneurs—especially women and SMEs—face unique challenges and pathways that have not been sufficiently theorized in clean energy contexts. Therefore, rather than assuming a linear link between resource mobilization and venture success, this study proposes that differentiated resource mobilization logics shape the competitiveness, inclusivity, and sustainability of green-tech ventures in Malaysia. We proposed:

H3. *Resource mobilization is positively associated with technopreneurial opportunities in the green hydrogen economy.*

2.6. Regulatory support and technopreneurial opportunities

Regulatory support refers to government policies, standards, and incentives that reduce uncertainty, promote investment, and enable the commercialization of innovation (Bradley et al., 2021; Marcus, 1981). In the context of green hydrogen, this support is particularly crucial due to the sector's emerging nature (Bade et al., 2024) and the need for clear frameworks around production standards (Brandt et al., 2024), transportation safety (Yazdi et al., 2023), subsidies, and carbon credits (Yang et al., 2024). Malaysia's Hydrogen Economy and Technology Roadmap sets ambitious targets for positioning the country as both a hydrogen exporter and domestic user, yet its fragmented implementation creates barriers for technopreneurs, who face unclear licensing processes, inconsistent safety guidelines, and limited integration with renewable energy policies.

Regulatory support encompasses not only financial mechanisms such as subsidies, tax incentives, and grants but also the institutional arrangements that shape market entry and legitimacy. For technopreneurs—who operate at the intersection of technology and market need—supportive regulation lowers barriers to experimentation, enhances opportunity recognition, and reduces entry risks in high-cost, high-uncertainty sectors (Chew et al., 2022). In clean energy, policies like feed-in tariffs, carbon pricing, and innovation grants have been shown to stimulate entrepreneurial activity by both reducing financial risk and signaling long-term government commitment (Xu et al., 2022; Zhao, Zhou, & Wen, 2021). However, empirical work in Malaysia highlights that while incentives such as the Green Technology Financing Scheme (GTFS) exist, their effectiveness is constrained by accessibility gaps, particularly for SMEs and emerging technopreneurs (Aleluia et al., 2022; Felker, 2025).

Beyond risk reduction, regulatory support legitimizes innovation by aligning entrepreneurial efforts with national sustainability priorities (Lian et al., 2022). In the green hydrogen economy, regulatory clarity enhances confidence among technopreneurs, investors, and ecosystem actors, which is vital given the sector's dependence on coordinated infrastructure and policy ecosystems. Yet, regulatory frameworks often lack gender sensitivity, inadvertently marginalizing female technopreneurs from institutional benefits and policy consultations (Chandel, 2022; Heuër, 2017). This exclusion not only perpetuates inequities but also weakens the inclusivity of Malaysia's clean energy transition, where diverse participation could expand innovation

pathways. Thus, we propose the following hypothesis;

H4. *Regulatory support is positively associated with technopreneurial opportunities in the green hydrogen economy.*

2.7. The entrepreneurial ecosystem and technopreneurial opportunities

The entrepreneurial ecosystem encompasses the interconnected actors, institutions, and processes that support entrepreneurship, including incubators, accelerators, educational institutions, financial systems, culture, and infrastructure (Kansheba & Wald, 2020; Malecki, 2018). For technopreneurs in the green hydrogen economy, the quality of the ecosystem significantly influences opportunity recognition and venture creation. A robust ecosystem provides access to technical training, mentorship, prototyping facilities, financing, market linkages, and collaborative networks (Audretsch & Link, 2019; Ferrandiz et al., 2018; O'Shea et al., 2021). In Malaysia, initiatives such as the National Technology and Innovation Sandbox (NTIS) demonstrate efforts to strengthen the innovation-driven ecosystem, but hydrogen-specific support mechanisms remain underdeveloped.

Empirical studies confirm that ecosystems play a pivotal role in fostering entrepreneurship by offering both tangible and intangible resources that help individuals recognize and act upon opportunities (Grande et al., 2023). In clean-tech and green-tech sectors, ecosystems connect entrepreneurs with government agencies, research institutions, venture capitalists, and large firms, thereby stimulating innovation and reducing market uncertainty (Pierrakis et al., 2024). This interconnectedness is especially critical in green hydrogen, where technological complexity, regulatory uncertainty, and high capital requirements make it difficult for isolated actors to succeed. Research also shows that Malaysia's clean energy SMEs thrive in regions with stronger innovation infrastructure, better university–industry linkages, and easier access to start-up financing (Islam et al., 2024). Moreover, ecosystems provide cultural and symbolic resources—such as visible role models and entrepreneurial norms—that shape perceptions of feasibility and desirability (Diepolder et al., 2024).

However, access to ecosystem resources is not equally distributed. Women are often underrepresented in incubators (Cukier et al., 2022), less visible in professional associations (O'Brien et al., 2019), and excluded from male-dominated networks in engineering and clean-tech fields (Cohn & Duncanson, 2023). These exclusions systematically disadvantage women technopreneurs by limiting their exposure to strategic information, mentorship, and collaborative opportunities, reinforcing gender gaps in green-tech entrepreneurship. An inclusive ecosystem—one that actively addresses such disparities—can therefore expand the spectrum of technopreneurial opportunities, enabling Malaysia's hydrogen transition to benefit from diverse perspectives and innovation pathways. Hence, we propose the following hypothesis:

H5. *A supportive entrepreneurial ecosystem is positively associated with technopreneurial opportunities in the green hydrogen economy.*

2.8. Technopreneurial opportunities and green-tech venture creation

Green-tech venture creation refers to the process by which entrepreneurs establish new businesses that develop or deploy environmentally sustainable technologies (Kim et al., 2023; Meyskens & Carsrud, 2013). In the context of the green hydrogen economy, these ventures aim to innovate across the hydrogen value chain—ranging from renewable-powered hydrogen production to storage, distribution, end-use applications, and digital integration (Akhtar et al., 2023). As global decarbonization accelerates, green hydrogen has become a crucial vector for sustainable energy transformation, offering fertile ground for venture development (Islam et al., 2024). However, despite this potential, green-tech venture creation in hydrogen faces structural barriers, including high capital intensity, fragmented markets, and the lack of a mature entrepreneurial ecosystem (Petkova et al., 2024; Zhang

et al., 2023). In Malaysia, early developments are concentrated among government-linked companies and large corporations (Mah et al., 2019), leaving smaller technopreneurs—particularly women—constrained by limited access to funding, mentorship, and strategic alliances (Munusamy et al., 2025).

Conceptually, technopreneurial opportunities are positioned as the immediate precursors to venture creation, distinct from regulatory support and entrepreneurial ecosystem, which function as external enabling conditions, and from SMR, which reflects the degree to which market conditions allow opportunities to be commercialized. This distinction clarifies that opportunities represent the actionable interface between internal capabilities and external environments.

The success of green-tech venture creation depends heavily on enabling conditions such as policy frameworks, institutional supports, and ecosystem readiness (Khan et al., 2025). Countries like Germany and South Korea have built hydrogen innovation clusters that connect research with commercialization (Lee & Kim, 2021; Quitzow et al., 2024), highlighting models Malaysia could adapt with localized inclusivity. Within this environment, technopreneurial opportunities serve as the critical bridge between technological possibilities and market realities. While prior entrepreneurship research has established the general link between opportunity recognition and venture creation (Kearney & Lichtenstein, 2023), this study extends the discussion by arguing that in the green hydrogen sector, opportunity recognition is uniquely shaped by environmental imperatives, regulatory transitions, and ecosystem inclusivity. This relationship is theoretically essential as it explains how identified opportunities are transformed into tangible ventures under conditions of technological uncertainty and institutional transition, thereby strengthening the causal pathway between opportunity and entrepreneurial outcomes.

Opportunity-driven entrepreneurship here is not merely about seizing market gaps, but about aligning business models with sustainability agendas, climate targets, and community acceptance, dimensions that are far less theorized in traditional entrepreneurship literature. Importantly, the conversion of opportunities into ventures is not uniform but contingent upon differential access to institutional support, networks, and scalable pathways, suggesting that the strength of this relationship may vary across gender. This highlights the need to interpret opportunity–venture linkages through differentiated pathways rather than treating gender as an isolated factor. Therefore, we propose the following hypothesis:

H6. *Technopreneurial opportunities are positively associated with green-tech venture creation in the green hydrogen economy.*

2.9. Technopreneurial opportunities and sustainable market readiness

SMR refers to the degree to which a market is equipped to adopt, support, and scale sustainable technologies and business models (Jutla et al., 2002; Nguyen & Duy Ha, 2024). Conceptually, SMR is distinct from institutional support (which primarily denotes formal regulatory frameworks and government rules) and ecosystem factors (which encompass the interconnected network of supportive actors, incubators, and resources). While institutional support and ecosystem factors reflect the presence of enabling conditions, SMR uniquely represents the outcome-oriented maturity and preparedness of the downstream market—such as demand certainty, commercial viability, and supply chain capacity—required to absorb these innovations. In the context of the green hydrogen economy, SMR acts as a critical bridge between technological potential and real-world commercialization (Abdin, 2024). Markets with high SMR address structural barriers—such as technological uncertainties, high capital intensity, fragmented regulations, and low public awareness (Patonia, 2025)—by fostering ecosystems that de-risk innovation, accelerate adoption, and enable the transition from pilot projects to large-scale deployment. Without such readiness, clean technologies risk remaining in the “valley of death,”

where promising innovations fail to scale.

In Malaysia, SMR is especially pivotal for positioning the country as a regional hydrogen hub. Despite abundant renewable resources, technical expertise, and strategic geography, the hydrogen sector risks underdevelopment unless SMR is enhanced through inclusive policy design, SME-focused financing, and integrated national infrastructure (Zakaria et al., 2023). Moreover, SMR must be gender-responsive. Studies show that women-led ventures face disproportionate barriers in accessing green finance, mentorship, and institutional support (Li et al., 2024; Ross & Shin, 2024). Thus, SMR should not only reduce systemic market frictions but also correct inequities that limit diverse entrepreneurial participation in the green hydrogen economy.

Markets become ready for green innovation when technopreneurs are able to translate scientific advancements into scalable business models that reshape both supply and demand dynamics (Halim et al., 2025). On the supply side, technopreneurs introduce novel solutions such as decentralized hydrogen production units, hydrogen-powered vehicles, AI-enabled distribution platforms, and blockchain-based hydrogen certification systems (Hakovirta, 2024; Mothafar et al., 2024). These innovations generate market learning, infrastructure experimentation, and consumer awareness, which are central elements of SMR. On the demand side, opportunity-driven entrepreneurship signals market potential to investors, regulators, and consumers, thereby catalyzing institutional alignment and accelerating policy momentum (Schaltegger et al., 2023).

In this sense, technopreneurial opportunities do not merely depend on SMR; they actively shape and expand it. By introducing viable, market-oriented green innovations, technopreneurs lower technology costs, stimulate consumer demand, and influence the policy agenda, thereby strengthening the very ecosystem required for further venture creation (Emon et al., 2025; Rathnayake & Roca, 2022). This reciprocal relationship suggests that SMR is not simply an external condition but also an emergent outcome of entrepreneurial activity in the green hydrogen sector. Therefore, the following hypothesis is proposed:

H7. *Technopreneurial opportunities are positively associated with sustainable market readiness in the green hydrogen economy.*

2.10. Sustainable market readiness and green-tech venture creation

Green-tech venture creation involves the formation of new businesses that commercialize environmentally friendly technologies. While, SMR provides this supportive environment by ensuring that the ecosystem elements such as supportive policies, market demand, infrastructure, financial instruments, and societal acceptance are in place. Empirical evidence suggests that high SMR positively influences green entrepreneurship outcomes. For instance, Capatina et al. (2024) and Mazzoni and Sedita (2025) highlight that in technology-intensive sustainability transitions, ventures succeed not solely because of their internal capacities but because of the maturity of the market ecosystem in which they are embedded. In markets with strong environmental regulation, accessible green finance, pilot programs, and public procurement support, green-tech ventures are more likely to emerge, scale, and achieve long-term sustainability.

SMR acts as a critical enabler of green-tech venture creation in the green hydrogen economy (Emon et al., 2025). It creates the necessary pull factors—such as market demand, infrastructure, regulatory backing, and investor interest—that complement the push from entrepreneurial innovation. Without SMR, even the most innovative green technologies may struggle to enter or succeed in the market. Therefore, we propose the following hypothesis:

H8. *Sustainable market readiness is positively associated with green-tech venture creation in the green hydrogen economy.*

2.11. Mediating effect of sustainable market readiness

The existence of technopreneurial opportunities does not automatically translate into the creation of viable green-tech ventures unless the market environment is ready to support, absorb, and scale these innovations. This is where SMR plays a mediating role. SMR empirically functions as a mechanism that transforms opportunity potential into entrepreneurial action. It includes factors such as policy alignment, availability of green finance, infrastructure readiness, market demand, and societal acceptance. Prior empirical studies have established that high market readiness increases the probability that green innovations will progress beyond the ideation stage (Borah et al., 2023; Putrevu et al., 2025). For instance, in countries with national hydrogen strategies and green procurement policies, the density of hydrogen-focused start-ups is higher compared to economies lacking those frameworks (Singh et al., 2025).

Conceptually, SMR is distinct from regulatory support and entrepreneurial ecosystem constructs, as it captures the outcome-oriented condition of market preparedness rather than the presence of institutional actors or support mechanisms. While regulatory support reflects formal rules and policies, and the entrepreneurial ecosystem represents networked actors and resources, SMR reflects the extent to which these elements converge to enable commercialization (Balachandra et al., 2010), thereby positioning it as a bridging construct between opportunity and venture creation.

Empirical studies have shown that opportunities alone are insufficient for venture creation unless embedded within a supportive ecosystem (Carter & Pezeshkan, 2023; Nair et al., 2022). For instance, in early-stage clean-tech sectors, even the most promising innovations may remain underdeveloped if markets lack readiness (Elf et al., 2025). SMR mitigates this gap by providing mechanisms that reduce uncertainty and improve the feasibility of venture creation, such as subsidies, pilot programs, tax incentives, green procurement, and knowledge platforms. This mediating relationship is theoretically essential as it explains how and under what conditions identified opportunities are converted into viable ventures, thereby strengthening the explanatory power of the model beyond direct effects.

Research by Rezaeian et al. (2024) on sustainability transitions and technology diffusion confirms that the presence of infrastructural support and policy incentives lowers transaction costs, accelerates customer acquisition, and enhances venture survival rates. Further, Shahid and Reynaud (2022) show that perceived market maturity positively moderates the relationship between environmental opportunity perception and entrepreneurial intention. The mediating role of SMR is critical: it operationalizes the potential of technopreneurial opportunities by creating an environment conducive to experimentation, adoption, and scaling. Without it, opportunities may remain latent; with it, they can catalyse a wave of sustainable, scalable green-tech ventures. Importantly, access to and benefits from market readiness conditions may vary across groups, as differences in access to finance, networks, and institutional channels can influence how effectively opportunities are translated into ventures. This suggests that the mediating effect of SMR may operate with varying strength across gendered pathways, reinforcing the need to consider differentiated mechanisms rather than treating gender as an isolated factor. Therefore, we propose the following hypothesis:

H9. *Sustainable market readiness mediates the relationship between technopreneurial opportunities and green-tech venture creation in the green hydrogen economy.*

2.12. Gender disparities

The rapid development of the green hydrogen economy is generating a wide array of technopreneurial opportunities—spanning innovative hydrogen production methods, storage technologies, fuel cell

development, and digital platforms for clean energy trading. While these emerging opportunities present immense potential for sustainable venture creation, not all individuals have equal access to leverage them. Gender continues to be a significant determinant in how opportunities are recognized, evaluated, and converted into entrepreneurial activity, particularly in male-dominated, capital-intensive sectors such as energy technology.

According to the Arias et al. (2023), women make up only 32% of the renewable energy workforce and even less in technical and executive roles. In Malaysia, although women account for a growing share of graduates in science and engineering, their participation in energy sector start-ups remains minimal (Serrano et al., 2023), indicating that gendered barriers persist in converting education into entrepreneurial action. Thus, the hypothesis posits a direct disparity: men are more likely than women to access and act upon technopreneurial opportunities in the green hydrogen sector, and this disparity contributes to a gender gap in green-tech venture creation. This relational proposition is supported by empirical research showing that male entrepreneurs are overrepresented in technology and engineering-based ventures, often due to better access to financial resources, technical networks, and policy channels (Kovaleva et al., 2023; Sperber & Linder, 2023).

From a resource-based perspective, opportunity access is influenced by ownership or control over strategic assets such as technical expertise, seed capital, and mentoring networks. Men tend to have greater access to these enablers in technology sectors, resulting in higher conversion of identified opportunities into start-ups (BarNir, 2012; Pugalia & Cetindamar, 2022). Thus, even when women identify opportunities within the green hydrogen value chain, they are less likely to pursue venture creation due to limited access to supporting resources.

Institutional Theory further explains that systemic structures—such as male-dominated funding mechanisms, STEM education pipelines, and policy ecosystems—embed gender biases that shape opportunity perception and exploitation. These institutional norms and values indirectly prioritize male participation in hydrogen tech ventures, reinforcing gender asymmetries in entrepreneurship (Osunmuyiwa & Ahlborg, 2022).

Moreover, the Gendered Ecosystem Perspective suggests that ecosystems are not gender-neutral; rather, they reflect societal power dynamics. For example, accelerator programs, clean-tech investment portfolios, and innovation hubs are often designed around male-centric norms of risk-taking, leadership, and technical competence. This implicit bias can create invisible barriers for women, even when policies claim inclusivity (Aman et al., 2024).

Therefore, it is hypothesized that men experience a systemic advantage in identifying, accessing, and acting on technopreneurial opportunities in the green hydrogen economy, which increases their likelihood of creating green-tech ventures compared to women. This gender gap is not simply a matter of individual differences but a result of structural inequalities embedded in the innovation and entrepreneurship landscape.

H10. *Gender disparities exist such that men have greater access to technopreneurial opportunities than women for green-tech venture creation in the green hydrogen economy.*

2.13. Conceptual framework

The conceptual framework of this study (see Fig. 1) illustrates the hypothesized relationships among technopreneurial opportunities, SMR, and green-tech venture creation. It is designed to capture how entrepreneurial capabilities and systemic enablers intersect to influence participation in Malaysia's emerging green hydrogen economy, particularly through the lens of gender inclusivity.

Before designing the framework, preliminary discussions were conducted with key stakeholders, including representatives from relevant ministries in Malaysia (such as the Ministry of Energy and Natural

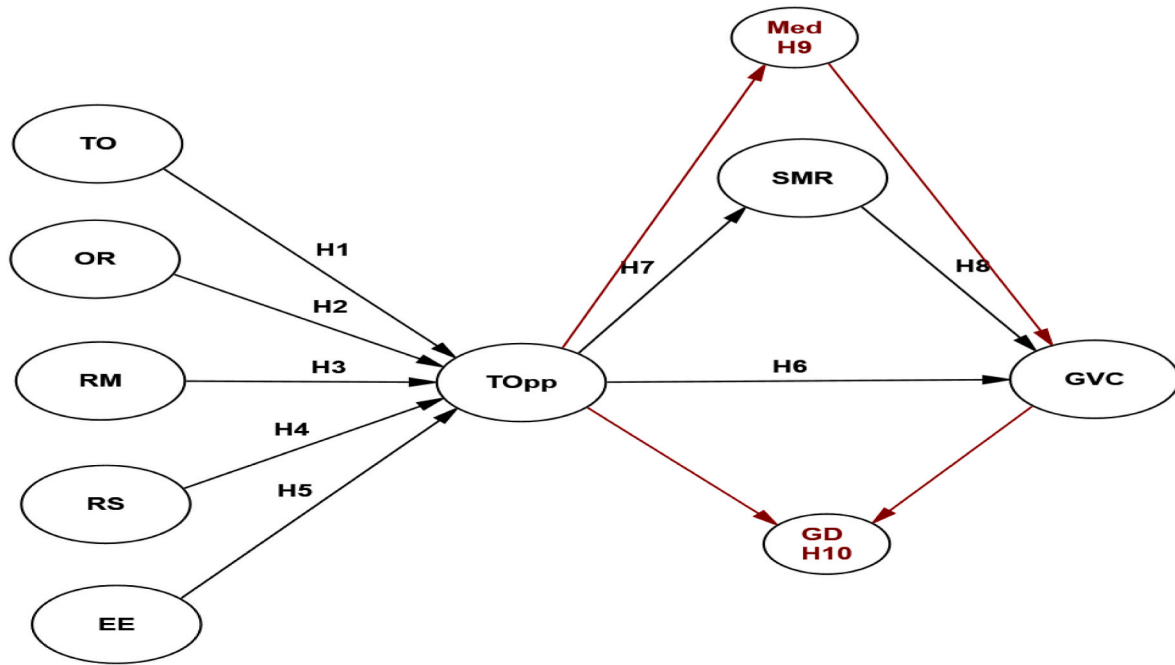


Fig. 1. Conceptual framework

Note: TO (Technopreneurial orientation), OR (Opportunity recognition), RM (Resource mobilization), RS (Regulatory support), EE (Entrepreneurial ecosystem), TOpp (Technopreneurial opportunities), SMR (Sustainable market readiness), GVC (Green-tech venture creation), Med (Mediating effect), and GD (Gender disparities).

Resources and the Ministry of Entrepreneur Development and Co-operatives), major industry players in the hydrogen and renewable energy sectors, established technopreneurs, early-stage entrepreneurs intending to venture into the green hydrogen economy, and women entrepreneurs from various backgrounds. These consultations provided grounded insights into real-world challenges, policy gaps, and ecosystem barriers—especially those affecting women's access to green-tech opportunities.

Drawing from these stakeholder perspectives, the framework was then informed by three core theoretical perspectives: Resource-Based View (RBV) highlights how access to strategic resources—such as knowledge, funding, and technology—enables technopreneurs to recognize and act on green opportunities. Institutional Theory emphasizes the importance of regulatory support and formal institutional structures in shaping entrepreneurial behaviour and innovation outcomes. Gendered Ecosystem Perspective recognizes that entrepreneurial ecosystems are not neutral; they often reflect gendered norms and structures that can disadvantage women in accessing resources, networks, and market opportunities.

Within this integrated framework, technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, and entrepreneurial ecosystem conditions are posited as key antecedents to technopreneurial opportunities. These opportunities, in turn, directly influence green-tech venture creation. The role of SMR is positioned as a mediator that enhances or conditions the pathway from opportunity recognition to successful venture creation.

The rationale for treating SMR as a mediator is twofold. First, SMR represents the set of systemic processes—such as infrastructure building, demand creation, financing mechanisms, and public awareness—that transform identified opportunities into viable ventures. In other words, SMR explains how and why technopreneurial opportunities translate into venture creation by bridging the gap between entrepreneurial intent and market adoption. Second, empirical and stakeholder evidence suggests that without market readiness, many promising opportunities remain latent, failing to progress into actual ventures. Thus, SMR is not merely a contextual condition that strengthens or weakens

the relationship (as a moderator would); rather, it is the mechanism through which opportunities materialize into ventures.

Furthermore, gender disparities are explicitly embedded in the model. The framework acknowledges that despite their potential, women technopreneurs may face structural and cultural disadvantages in leveraging opportunities, navigating the entrepreneurial ecosystem, and scaling green-tech ventures—especially in a male-dominated and capital-intensive sector like green hydrogen.

3. Methodology

3.1. Questionnaire design

To empirically examine the proposed conceptual framework, a structured questionnaire comprising two distinct sections was meticulously developed. Section A was designed to collect essential demographic and background information from the respondents. This section included questions related to gender, age, education level, professional background, type of business involvement, and prior experience in entrepreneurship or the energy sector. These demographic variables are critical for understanding the profile of the participants and for enabling subgroup analyses, particularly in exploring gender disparities in technopreneurial opportunities.

Section B of the questionnaire was dedicated to assessing the key constructs derived from the study's integrated theoretical framework. This section comprised a series of closed-ended items aimed at measuring constructs such as technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, entrepreneurial ecosystem, SMR, and green-tech venture creation. Each item in this section was measured using a 7-point Likert scale, ranging from “strongly disagree” (1) to “strongly agree” (7), to capture varying degrees of respondent agreement and to ensure adequate sensitivity in the data. The scale facilitates a nuanced understanding of participants' perceptions, attitudes, and experiences regarding the green hydrogen economy and their readiness and ability to engage in green-tech venture creation.

3.2. Pilot testing and validation

To ensure the reliability, clarity, and content validity of the measurement instrument, a pilot test was conducted prior to the full-scale data collection. The primary aim of the pilot study was to evaluate the internal consistency of the items, assess their clarity and relevance to the Malaysian green hydrogen context, and refine the questionnaire based on expert feedback. This step was crucial for enhancing the instrument's psychometric robustness and contextual appropriateness.

The pilot test involved 20 subject-matter experts with substantial experience in areas such as green technology, entrepreneurship, sustainable energy policy, and innovation management. These experts were drawn from academia, industry, and government agencies directly involved in clean energy initiatives and SME development in Malaysia. Their involvement ensured a balanced evaluation of the instrument from both theoretical and practical perspectives.

The experts were asked to review the questionnaire in terms of clarity of language, comprehensiveness of content, and relevance of each item to the constructs of the study. Feedback was collected using both structured ratings and open-ended comments. As a result of the pilot test, 5 items were eliminated due to redundancy, ambiguity, or weak relevance to the construct they were intended to measure. These items were either conceptually overlapping with others. Thus, out of the original 43 measurement items, a refined total of 38 items were retained for the final survey instrument. The retained items demonstrated adequate face validity and were deemed clear, contextually appropriate, and well-aligned with the study's conceptual framework.

Furthermore, preliminary reliability analysis (Cronbach's alpha) conducted on the pilot data showed that all constructs—Technopreneurial Orientation ($\alpha = 0.88$), Opportunity Recognition ($\alpha = 0.91$), Resource Mobilization ($\alpha = 0.89$), Regulatory Support ($\alpha = 0.86$), Entrepreneurial Ecosystem ($\alpha = 0.83$), SMR ($\alpha = 0.91$), and Green-tech Venture Creation ($\alpha = 0.92$)—achieved acceptable reliability thresholds ($\alpha > 0.70$), indicating good internal consistency. In the final analysis, the statistical validation further confirmed these results: Cronbach's alpha values for all constructs remained above .70 and the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was .84, exceeding the recommended .60 threshold. These findings collectively demonstrate that the constructs possess strong internal consistency, adequate sampling adequacy, and factorability, thereby reinforcing the robustness of the measurement model.

3.3. Questionnaire translation

To ensure linguistic clarity and cultural appropriateness for the target respondents in Malaysia, a rigorous translation process was carried out for the study's structured questionnaire. The original instrument, initially developed in English, was translated into Bahasa Malaysia to accommodate the primary language preferences of local participants, especially among grassroots entrepreneurs, SME owners, and early-stage technopreneurs who may not be fully fluent in English.

The questionnaire followed a forward–backward translation procedure, widely recognized for enhancing translation reliability in cross-cultural research (Cruchinho et al., 2024). First, a professional bilingual translator with expertise in business and energy-sector terminology translated the full questionnaire from English into Bahasa Malaysia. After the initial translation, the Bahasa Malaysia version was reviewed by three independent bilingual experts in entrepreneurship and clean energy policy to assess its clarity, cultural relevance, and linguistic accuracy. Following data collection, the completed responses in Bahasa Malaysia were translated back into English by a separate team of bilingual translators who had not been involved in the original translation.

To establish measurement equivalence, pre-testing was conducted with a pilot group of 30 bilingual respondents who completed both English and Bahasa Malaysia versions. Paired-sample t-tests and

correlation analyses showed no significant differences in item means across the two versions, confirming semantic and conceptual alignment. In addition, confirmatory factor analysis (CFA) indicated consistent factor loadings across languages, supporting cultural validity of the constructs. As a result, the final instrument was deemed reliable and appropriate for use in both English and Bahasa Malaysia versions (refer to Appendix A and B), supporting the study's goal of inclusivity and contextual accuracy within the Malaysian technopreneurial landscape.

3.4. Sample and procedure

This study employed a quantitative, cross-sectional survey method to collect primary data from current and aspiring technopreneurs operating or interested in green-tech venture creation within Malaysia's emerging green hydrogen economy. To ensure representativeness and geographic diversity, the sampling framework included respondents from both East Malaysia (Sarawak and Sabah) and West Malaysia—specifically the states of Perlis, Kedah, Penang, Perak, Selangor, Johor, and the Federal Territory of Kuala Lumpur. These regions were selected due to their strategic importance in renewable energy development, SME activity, and entrepreneurship policy initiatives, as well as to reflect Malaysia's demographic and economic diversity.

The study employed a stratified random sampling technique to ensure balanced and adequate representation across key subgroups, including gender, business sectors, and regions, which are theoretically relevant to technopreneurial opportunity formation. Given the heterogeneous and emerging nature of the green hydrogen ecosystem, simple random sampling could risk underrepresenting smaller yet critical sub-populations; thus, stratification enhances the precision and comparability of results by proportionally including each subgroup and supporting more reliable multi-group analysis, particularly for gender-based comparisons. Within each stratum, technopreneurs were identified through professional networks, entrepreneurship incubators, SME associations, clean energy events, and government-linked programs that support sustainable innovation. While this approach was designed to maximize diversity and inclusivity, it is acknowledged that the final sample may not fully represent the broader population of Malaysian entrepreneurs in the green hydrogen and clean-tech sectors, given the nascent and highly specialized nature of this field.

To determine the appropriate sample size, the study referred to Krejcie and Morgan's (1970) sample size determination table. Given the estimated population of technopreneurs and SME actors across the selected regions, the minimum required sample size was calculated to be approximately 384 respondents for a confidence level of 95% and a margin of error of 5%. However, to account for potential non-responses and incomplete surveys, the study aimed to distribute over 500 questionnaires.

The data collection process involved both online and offline distribution methods. Online surveys were administered through a secure platform and disseminated via email and social media channels targeting technopreneurial communities. Offline distribution included hard copies handed out during entrepreneurship workshops and renewable energy forums, particularly in semi-urban and rural areas of East Malaysia where digital access may be limited.

Prior to data collection, informed consent was obtained from all participants. The purpose of the study, their rights as respondents, and the confidentiality of their responses were clearly communicated. Participation was entirely voluntary, and respondents were assured that their identities would remain anonymous and that their data would be used solely for academic research purposes.

Out of the 500 surveys distributed, a total of 431 valid responses were received, yielding a response rate of 86.1%. This high response rate reflects the relevance and timeliness of the research topic among Malaysia's technopreneurial community. The final sample included a diverse range of participants in terms of gender, business maturity levels, sectors, and regional locations, providing a comprehensive

dataset for rigorous statistical analysis and meaningful insights into the dynamics of green-tech venture creation in Malaysia's green hydrogen economy. However, because these data are cross-sectional, certain methodological boundaries must be recognized. Since all variables were gathered at a single point in time, the structural model findings must be interpreted strictly as statistical associations rather than dynamic, temporal causality. Furthermore, because the survey relies on self-reported perceptions from a single respondent source, the data may be susceptible to potential common method bias (CMB) and social desirability effects. To address and mitigate these concerns, procedural design remedies—such as ensuring complete participant anonymity and randomizing item ordering—were implemented.

3.5. Measures

3.5.1. Aspects of technopreneurial opportunities

To examine the factors influencing technopreneurial opportunities in the context of the green hydrogen economy, this study measured five key constructs: technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, and the entrepreneurial ecosystem. These variables were selected based on their theoretical relevance to green-tech entrepreneurship and their demonstrated significance in prior empirical studies. The operational definitions and measurement details of the constructs are as follows:

- *Technopreneurial orientation* in this study is defined as the extent to which technopreneurs demonstrate innovative, proactive, and risk-taking behaviour in pursuing technology-driven opportunities within the green hydrogen economy.
- *Opportunity recognition* in this study is defined as the ability of technopreneurs to identify and evaluate viable market needs and technological gaps in the green hydrogen sector and translate them into actionable business opportunities.
- *Resource mobilization* in this study is defined as the ability of technopreneurs to acquire and effectively leverage financial, human, and technical resources to initiate and sustain green-tech ventures in the hydrogen economy.
- *Regulatory support* in this study is defined as the extent to which government policies, incentives, and institutional frameworks facilitate the growth of technopreneurial ventures in the green hydrogen economy.
- *Entrepreneurial ecosystem* in this study is defined as the network of stakeholders, institutions, and support systems that collectively influence technopreneurial activity in the green hydrogen economy.

To assess the constructs, twenty-seven items were adapted from validated scales in prior studies, ensuring strong content validity and contextual alignment with the Malaysian green hydrogen economy. These measurement items were drawn from the studies of Zeng et al. (2022), Capatina et al. (2024), Bagheri (2017), Guo et al. (2016), Patnaik and Tarei (2022), Kahpi et al. (2024), Chatterjee et al. (2021), Elnadi and Gheith (2021), and Festa et al. (2023). By leveraging these established instruments, the study ensures methodological rigor while tailoring the content to the local entrepreneurial landscape. These adapted items allow for a comprehensive evaluation of the key enabling factors that shape technopreneurial opportunities in Malaysia's evolving green hydrogen ecosystem.

3.5.2. Sustainable market readiness

SMR refers to the extent to which the market environment—comprising demand maturity, infrastructure, policy alignment, consumer awareness, and supply chain capacity—is prepared to support the successful launch and scaling of green-tech ventures. Within the green hydrogen economy, SMR reflects the alignment of environmental sustainability goals with market dynamics and innovation capabilities that enable technopreneurs to enter and thrive in the

ecosystem.

To measure this construct, seven items were adapted from established, validated instruments used in prior research. These include seminal and relevant studies by Nguyen and Duy (2024) and Gerdtsri and Manotungvorapun (2021). The selection of items was based on their relevance to assessing market receptiveness, infrastructure maturity, policy effectiveness, and environmental alignment in the context of sustainable technological ventures.

3.5.3. Green-tech venture creation

Green-tech venture creation refers to the process by which technopreneurs initiate, develop, and scale environmentally sustainable business ventures, particularly those leveraging green hydrogen technologies. In the context of this study, it encompasses the entrepreneurial efforts aimed at establishing businesses that contribute to low-carbon innovations, clean energy solutions, and environmental sustainability through the use of hydrogen as a key enabler.

To measure this construct, seven items were carefully adapted from established and validated scales used in previous empirical studies, most notably by Bhardwaj et al. (2024) and Khurshed and Mustafa (2024). These studies provided a foundational basis for assessing technology-driven entrepreneurial behaviours and innovation-oriented business creation, ensuring that the adapted items are both psychometrically sound and contextually relevant for Malaysia's emerging green hydrogen sector.

3.6. Statistical analysis

To test the proposed hypotheses and examine the interrelationships among the latent constructs, this study adopted a two-step Structural Equation Modeling (SEM) approach, using AMOS version 28.0. SEM was chosen for its ability to evaluate complex causal relationships while accounting for measurement error across multiple constructs (Hair & Alamer, 2022). This approach enabled the study to simultaneously assess both the measurement model and the structural model, thereby ensuring a rigorous evaluation of construct validity and the hypothesized relationships.

In the first step, Confirmatory Factor Analysis (CFA) was conducted to assess the validity and reliability of the measurement model. All items were examined for their standardized factor loadings, with values above .60 retained. Construct reliability was verified through Composite Reliability (CR) scores exceeding .70, and Average Variance Extracted (AVE) values above .50 were used to establish convergent validity. Discriminant validity was assessed using the Heterotrait-Monotrait ratio (HTMT).

Model fit indices were also examined to confirm the adequacy of the measurement model. Specifically, the following thresholds were adopted: χ^2/df values less than 3.0 (indicating acceptable fit), Comparative Fit Index (CFI) and Tucker–Lewis Index (TLI) values greater than .90 (preferably above .95), Root Mean Square Error of Approximation (RMSEA) values less than .08 (with values below .05 indicating close fit), and Standardized Root Mean Square Residual (SRMR) values below .08. These indices collectively ensured a comprehensive evaluation of model fit beyond reliance on a single metric.

Once the measurement model demonstrated satisfactory validity and reliability, the second step involved evaluating the structural model to test the hypothesized causal relationships between the constructs. This stage allowed the study to evaluate the direct effects of the independent variables (e.g., technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, and entrepreneurial ecosystem) on technopreneurial opportunities, and the impact of those opportunities on green-tech venture creation. Additionally, the mediating role of SMR was assessed to understand its influence on the translation of technopreneurial opportunities into actual venture outcomes.

To evaluate the mediating effect of SMR, a bootstrapping method

was employed using 1000 resamples and a 95% bias-corrected confidence interval. This technique provides more robust estimates of indirect effects compared to traditional approaches. The mediation was considered significant if the confidence interval for the indirect effect did not include zero. It is important to acknowledge the methodological limitations of using SEM with cross-sectional data. While SEM allows testing of complex causal relationships, cross-sectional designs restrict the ability to infer temporal causality or dynamic changes over time. Consequently, the findings should be interpreted as associational rather than strictly causal.

To investigate gender disparities in the green hydrogen economy, particularly regarding access to technopreneurial opportunities and green-tech venture creation, a Multi-Group Analysis (MGA) was conducted by dividing the sample into male and female groups. Prior to comparing path differences, measurement invariance testing was performed to ensure the constructs were equivalent across groups. Following established procedures (Byrne, 2016; Hair & Alamer, 2022), the analysis proceeded in stages: first, configural invariance was established by testing a baseline model for both groups, confirming that the same factor structure applied. Next, metric invariance was assessed by constraining factor loadings, which verified that males and females interpreted the constructs similarly. Scalar invariance was then examined by constraining intercepts, ensuring that mean differences across groups reflected true latent differences rather than measurement bias. Once metric and scalar invariance were confirmed, path differences were examined to evaluate whether the hypothesized relationships varied across gender. The analysis specifically explored (i) how technopreneurial orientation and opportunity recognition translated into perceived opportunities, (ii) whether SMR mediated these relationships differently for male and female technopreneurs, and (iii) disparities in the likelihood of converting opportunities into green-tech ventures. This rigorous multi-group approach thus provided empirical insights into systemic gender differences and offered a more nuanced understanding of why female technopreneurs may face greater challenges in leveraging opportunities within Malaysia's green hydrogen economy.

4. Results

4.1. Demographic profile of participants

Table 1 presents the demographic profile of the respondents who participated in this study, offering a comprehensive overview of the sample characteristics. Given the study's specific focus on gender disparities, particular effort was made to ensure sufficient representation of female entrepreneurs or women with intentions to engage in green hydrogen-related ventures. As a result, the sample included 221 male respondents (51.3%) and 210 female respondents (48.7%), ensuring a balanced gender distribution suitable for comparative analysis. The majority of participants (74.7%) fell within the 25–44 age group, reflecting a relatively young and dynamic entrepreneurial segment actively engaged in or exploring green-tech opportunities.

A substantial proportion of respondents were married (71.0%), and educational attainment was generally high, with 51% of participants holding at least a bachelor's degree—underscoring the relevance and readiness of the sample to engage with the knowledge-driven green hydrogen sector. Ethnically, the sample mirrored Malaysia's multicultural landscape, with the majority comprising Malay (34.6%) and Chinese entrepreneurs (39.9%), alongside Indian and indigenous participants. In terms of business ownership status, 62.9% of respondents identified as sole proprietors, highlighting the predominance of individually-led ventures in the green-tech space.

Sectoral representation showed a diverse entrepreneurial landscape, with respondents operating primarily in the service (45%), manufacturing (25%), and energy (20%) sectors—industries most likely to be impacted by or contribute to the green hydrogen transition. Notably, 70.8% of participants reported having more than three years of

Table 1
Demographic assessment.

Characteristics		Number	Percentage
Gender	Male	221	51.3%
	Female	210	48.7%
Age	18 - 24	13	3.0%
	25 - 34	139	32.3%
	35 - 44	183	42.4%
	45 - 54	74	17.2%
	55 and above	22	5.1%
Marital status	Single	78	18.1%
	Married	306	71.0%
	Widow	11	2.6%
	Divorced	36	8.3%
Highest Educational Qualification	Secondary School	18	4.2%
	Diploma	106	24.6%
	Bachelor's degree	220	51.0%
	Master's degree	82	19.0%
Ethnicity	Doctorate	5	1.2%
	Malay	149	34.6%
	Chinese	172	39.9%
	Indian	57	13.2%
	Indigenous (e.g., Iban, Kadazan-Dusun)	45	10.4%
	Others	8	1.9%
Business Ownership Status	Sole Proprietor	271	62.9%
	Partnership	98	22.7%
	Private Limited (Sdn. Bhd.)	34	7.9%
	Not currently a business owner	28	6.5%
Type of Business Sector	Manufacturing	108	25.0%
	Services	194	45.0%
	Agriculture	36	8.4%
	Energy/Green Tech	86	20.0%
	Others	7	1.6%
Years of Entrepreneurial Experience	Less than 1 year	39	9.0%
	1–3 years	87	20.2%
	4–6 years	235	54.5%
	More than 6 years	70	16.3%
Geographical Location of Business	East Malaysia (Sarawak/Sabah)	183	42.5%
	West Malaysia	248	57.5%

entrepreneurial experience, offering a mature and informed perspective on the process of green-tech venture creation. Furthermore, regional representation was well balanced, with 42.5% of respondents from East Malaysia and 57.5% from West Malaysia, thereby capturing the geographic and infrastructural diversity relevant to Malaysia's evolving green hydrogen economy.

4.2. Normality statistics

To ensure the robustness of the SEM analysis using AMOS, it was essential to first examine the normality of the dataset. Normality testing is a crucial prerequisite in SEM as it influences the accuracy of parameter estimates and model fit indices (Dash & Paul, 2021). In this study, both univariate and multivariate normality assessments were conducted. For univariate normality, skewness and kurtosis values of all items were examined, with acceptable thresholds ranging between +3 and −3 (Busse & Jelly, 2023). The results confirmed that the dataset met the assumptions of univariate normality, as all values fell within the required range.

Subsequently, multivariate normality tests were conducted to determine whether the dataset exhibited an overall multivariate normal distribution. The outcomes of these tests, as summarized in Table 2, indicated that the dataset conformed to the assumptions of multivariate normality. Specifically, cases demonstrated multivariate kurtosis values within the +3 to −3 range and critical ratio values below 1.96 (Cain et al., 2017), satisfying the criteria necessary for valid SEM analysis. These findings confirmed the suitability of the data for subsequent confirmatory factor analysis (CFA) and structural model evaluation in

Table 2
Normality assessment.

Variables	Mean	Std. Dev.	Skewness	c.r.	Kurtosis	c.r.
TO	6.05	.39	.062	.896	.117	.974
OR	5.38	.36	.293	1.753	.072	.283
RM	5.82	.47	.078	.931	.325	1.018
RS	6.16	.53	.457	1.802	.166	.789
EE	5.29	.35	-.051	-.568	.039	.207
SMR	6.24	.62	.706	1.912	-.197	-.832
GVC	5.72	.57	.086	.141	-.226	-.785
Multivariate					.296	.454

AMOS.

4.3. Assessment of discriminant validity

Discriminant validity is a critical criterion in SEM as it ensures that each construct in the model is distinct and captures phenomena not represented by other constructs (Henseler et al., 2015). To assess discriminant validity in this study, the Heterotrait-Monotrait (HTMT) ratio of correlations was employed, which is widely regarded as a more rigorous and reliable method than traditional approaches. Following the recommendation by Voorhees et al. (2016), an HTMT threshold value of .85 was adopted. This means that an HTMT value below .85 between any two constructs indicates that discriminant validity has been established. As shown in Table 3, all HTMT values in this study were below the .85 threshold, confirming that the constructs are empirically distinct from one another and that the model possesses adequate discriminant validity.

4.4. Assessment of Confirmatory Factor Analysis (CFA)

CFA was employed to evaluate the measurement model and ensure that the observed items adequately reflected the underlying latent constructs in the study (Marsh et al., 2020). As part of the model refinement process, several items were removed due to insufficient factor loadings, which fell below the recommended threshold of .70. Specifically, one item was removed from the Technopreneurial Orientation construct, one from the Entrepreneurial Ecosystem, and one from SMR. These adjustments were crucial for enhancing the model's convergent validity and achieving an acceptable fit.

Following the refinement, all retained items exhibited factor loadings exceeding the .70 benchmark, indicating strong individual item reliability. The revised measurement model is illustrated in Fig. 2 and provides a robust representation of the underlying constructs.

Model fit indices were evaluated to determine the adequacy of the measurement model. The fit statistics were as follows: Root Mean Square Error of Approximation (RMSEA) = .062, Chi-square (χ^2) = 427.167 with degrees of freedom (df) = 412, Goodness-of-Fit Index (GFI) = .908, Adjusted Goodness-of-Fit Index (AGFI) = .927, Comparative Fit Index (CFI) = .939, and the chi-square to degrees of freedom ratio (CMIN/df) = 3.018. These values fall within the acceptable range as suggested by Al-Fadhali (2024), indicating that the measurement model demonstrated a satisfactory fit with the observed data.

As part of the measurement model evaluation, CFA was conducted to

Table 3
Heterotrait-monotrait ratio of correlations.

Variables	1	2	3	4	5	6	7
TO	1						
OR	.43	1					
RM	.41	.47	1				
RS	.44	.38	.35	1			
EE	.46	.42	.37	.31	1		
SMR	.52	.46	.48	.39	.58	1	
GVC	.59	.41	.36	.52	.43	.57	1

assess the reliability and validity of the constructs included in the study. Specifically, construct validity was evaluated using two key metrics: Average Variance Extracted (AVE) and Composite Reliability (CR). These measures offer critical insights into the extent to which observed indicators represent their respective latent constructs.

Average Variance Extracted (AVE) is used to assess convergent validity by determining how much variance in the observed variables is captured by the latent construct relative to the variance due to measurement error. According to Cheung et al. (2024), AVE values should exceed the threshold of .50 to confirm acceptable convergent validity. In this study, as reported in Table 4, all constructs recorded AVE values above .50, indicating that each construct explains more than half of the variance in its associated indicators.

Composite Reliability (CR) was also examined to evaluate the internal consistency of each construct. A CR value above .70, as recommended by Cheah et al. (2018), demonstrates that the set of items measuring a latent construct are reliable and consistently represent the construct. In this study, the CR values for all constructs exceeded the .70 benchmark, thus confirming the high reliability of the measurement model.

The results, summarized in Table 4, provide strong evidence that the measurement model exhibits both convergent validity and internal consistency. Together, the AVE and CR findings confirm that the constructs used in the study are both reliable and valid, thereby affirming the robustness of the CFA model and its suitability for subsequent structural model testing.

4.5. Assessment of structural model

The structural model was assessed to examine the hypothesized relationships among the latent constructs proposed in the conceptual framework. According to S. Davcik(2014), evaluating the structural model is a critical step in SEM as it enables researchers to determine whether the hypothesized paths among constructs are supported by the empirical data. This step follows a successful CFA and provides insights into the causal relationships within the model.

As illustrated in Fig. 3, the structural model demonstrated an excellent fit with the observed data, aligning with the model fit criteria recommended by Hair and Alamer (2022). The goodness-of-fit indices confirmed the adequacy of the model. Specifically, the chi-square value was 4.132, with the following additional fit indices: GFI = .938, AGFI = .927, CFI = .949, TLI = .943, and the RMSEA = .051. These values indicate that the model is well specified and fits the data excellently, with all indices falling within or exceeding the accepted thresholds (GFI, AGFI, CFI, TLI > .90; RMSEA < .08).

In this study, the research model proposed a total of ten hypotheses, eight of which examined direct relationships among the constructs. These direct hypotheses were tested using SEM, with a focus on analysing the standardized path coefficients (β values) and their corresponding p-values to determine statistical significance. This analytical approach facilitated the evaluation of both the strength and direction of influence among the independent and dependent variables within the proposed theoretical model.

As presented in Table 5, all eight direct hypotheses—H1 through H8—were empirically supported, demonstrating statistically significant and robust relationships among the study's key constructs. H1 was supported ($\beta = .38$, $z = 4.791$, $p < 0.001$), indicating that technopreneurial orientation has a moderately strong positive effect on technopreneurial opportunities. In practical terms, this means that individuals and firms who demonstrate higher levels of innovation, proactiveness, and risk-taking are about 38% more likely to convert these attributes into viable opportunities in the green hydrogen economy.

H2 was supported ($\beta = .35$, $z = 4.508$, $p < 0.001$), suggesting that opportunity recognition significantly enhances technopreneurial opportunities. A coefficient of .35 reflects a meaningful effect, showing that entrepreneurs who are alert to emerging market gaps and

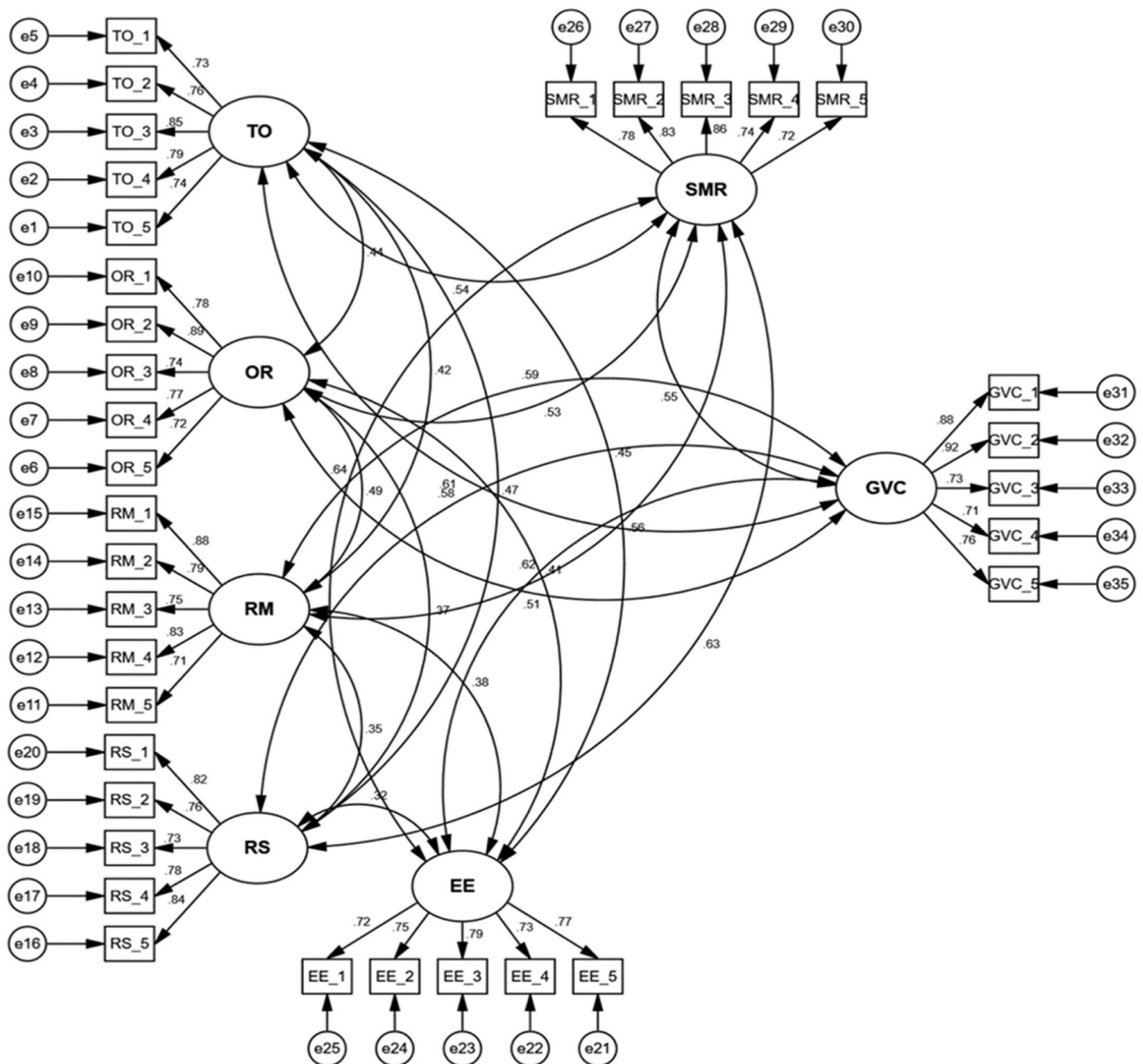


Fig. 2. Overall measurement model.

technological trends can substantially increase their likelihood of identifying opportunities within Malaysia's nascent green hydrogen sector.

H3 was supported ($\beta = .41$, $z = 5.116$, $p < 0.001$), confirming that resource mobilization exerts a strong positive impact on technopreneurial opportunities. The effect size indicates that effective access and coordination of financial, human, and technical resources boost the ability to capitalize on green hydrogen-related opportunities by 41%, underscoring the critical role of resource availability in this capital-intensive sector.

H4 was supported ($\beta = .39$, $z = 4.963$, $p < 0.001$), highlighting that regulatory support significantly contributes to opportunity formation. This implies that entrepreneurs operating in environments with favourable policies, tax incentives, and institutional backing are 39% more likely to identify and pursue opportunities in green hydrogen, reinforcing the importance of policy interventions in shaping

entrepreneurial activity.

H5 was supported ($\beta = .43$, $z = 5.455$, $p < 0.001$), showing that a supportive entrepreneurial ecosystem has the strongest effect among the predictors on opportunity recognition. This coefficient suggests that robust networks of mentors, investors, institutions, and support services increase the likelihood of opportunity creation by 43%, reflecting the centrality of ecosystem quality in sustaining entrepreneurial momentum in emerging industries like green hydrogen.

H6 was supported ($\beta = .27$, $z = 3.872$, $p < 0.001$), indicating that technopreneurial opportunities translate into green-tech venture creation, though with a relatively modest effect size. This suggests that while opportunities are important, additional enablers (such as market readiness) are required to fully realize venture creation.

H7 was supported ($\beta = .53$, $z = 6.521$, $p < 0.001$), revealing that technopreneurial opportunities strongly predict SMR. With the highest coefficient in the model, this indicates that opportunity recognition not

Table 4
CR and AVE evaluation.

Variables	Items	Factor Loading	CR	AVE
TO	TO_1	.73	.882	.601
	TO_2	.76		
	TO_3	.85		
	TO_4	.79		
	TO_5	.74		
OR	OR_1	.78	.887	.612
	OR_2	.89		
	OR_3	.74		
	OR_4	.77		
	OR_5	.72		
RM	RM_1	.88	.895	.631
	RM_2	.79		
	RM_3	.75		
	RM_4	.83		
	RM_5	.71		
RS	RS_1	.82	.890	.619
	RS_2	.76		
	RS_3	.73		
	RS_4	.78		
	RS_5	.84		
EE	EE_1	.72	.867	.566
	EE_2	.75		
	EE_3	.79		
	EE_4	.73		
	EE_5	.77		
SMR	SMR_1	.78	.891	.621
	SMR_2	.83		
	SMR_3	.86		
	SMR_4	.74		
	SMR_5	.72		
GVC	GVC_1	.88	.901	.647
	GVC_2	.92		
	GVC_3	.73		
	GVC_4	.71		
	GVC_5	.76		

only drives entrepreneurial intent but also significantly enhances the preparedness of markets to absorb and support green hydrogen ventures in Malaysia.

H8 was supported ($\beta = .58$, $z = 6.954$, $p < 0.001$), confirming that SMR is the strongest predictor of green-tech venture creation. The coefficient of .58 underscores its practical importance, meaning that as markets mature—through infrastructure, demand, and policy alignment—the likelihood of successful venture creation increases by nearly 60%.

4.6. Assessment of mediating effect

The mediating role of SMR between technopreneurial opportunities and green-tech venture creation was rigorously examined in this study, providing strong empirical support for Hypothesis 9 (H9). This hypothesis posited that SMR serves as a significant intermediary mechanism through which technopreneurial opportunities influence green-tech venture creation in the context of Malaysia's green hydrogen economy.

Following the complementary mediation criteria articulated by Zhao et al. (2010), both the direct and indirect pathways were analysed. The standardized path coefficients for the direct path (technopreneurial opportunities → green-tech venture creation) and the indirect path (technopreneurial opportunities → SMR → green-tech venture creation) were found to be positive and statistically significant. These findings suggest a complementary mediation effect, where SMR not only partially transmits the influence of technopreneurial opportunities but also reinforces their overall impact on the creation of green-tech ventures.

To enhance the robustness of the mediation analysis, a bootstrap resampling procedure was conducted with 1000 iterations at a 95% confidence interval, as recommended by Alfons, Ateş, and Groenen

(2022). This approach was employed to improve the precision and credibility of the parameter estimates. The results of the bootstrapping procedure, as presented in Table 6, confirmed the significance of the indirect effects, thereby validating the mediating role of SMR.

The coefficient for the first path (TOpp → SMR: $\beta = .56$) indicates that a one standard deviation increase in technopreneurial opportunities leads to a 56% increase in SMR. In real-world terms, this suggests that as entrepreneurs in Malaysia's green hydrogen sector identify and pursue more opportunities, markets become substantially more prepared—through improved infrastructure, demand signals, and institutional alignment—to support green-tech ventures. The second path (SMR → GVC: $\beta = .61$) demonstrates that SMR is a very strong predictor of venture creation. A one standard deviation increase in SMR boosts green-tech venture creation by 61%, showing that even when entrepreneurs recognize opportunities, successful commercialization and scaling are highly dependent on whether the market ecosystem is mature enough to absorb these innovations. This underscores the critical role of policy alignment, financing structures, and consumer adoption in turning opportunities into viable businesses.

4.7. Assessment of multi-group analysis

To investigate gender disparities in the translation of technopreneurial opportunities into green-tech venture creation, this study employed a multi-group SEM analysis. This analytical strategy was guided by the recommendation of Kuhlemeier and Willging (2024), who highlighted the utility of multi-group SEM in identifying systematic differences across subpopulations. In the context of this study, the aim was to assess whether the proposed model operates differently for male and female technopreneurs, particularly with regard to the green-tech venture creation.

In accordance with the guidelines proposed by Chiorri et al. (2016), an invariance testing strategy was implemented to determine whether the measurement and structural parameters of the model were equivalent across gender groups. This process is critical to ensure that any observed group differences are not artifacts of measurement inconsistencies.

The analysis began with testing factor loadings (i.e., metric invariance) across the male and female groups. The chi-square difference test yielded a statistically significant result ($\text{CMIN} = 73.51$, $p < 0.05$), indicating that the loadings differed between the two groups. This suggests that men and women may interpret the construct indicators differently, which has implications for how technopreneurial orientation and other antecedents are internalized and acted upon.

Following this, the structural parameter invariance was assessed to determine whether the hypothesized relationships between constructs varied by gender. Again, the chi-square difference test revealed a significant result ($\text{CMIN} = 51.18$, $p < 0.05$), supporting the presence of gender-based differences in the structural pathways. Specifically, the strength of the relationships among technopreneurial opportunities, SMR, and green-tech venture creation varied between male and female respondents, confirming that gender plays a role in shaping how these constructs interact in practice.

In contrast, the analysis of factor correlations between the constructs showed invariance across gender groups. The chi-square difference between the baseline and constrained models was non-significant ($\text{CMIN} = 3.96$, $p > 0.05$), indicating that the correlations among constructs such as technopreneurial orientation, opportunity recognition, and regulatory support are perceived similarly by both male and female respondents. This consistency supports the theoretical robustness of the model while allowing for nuanced differences in specific path relationships.

The detailed results of the multi-group invariance tests are summarized in Table 7, which confirms that while the structural effects and factor loadings show gender-based variation, the overall conceptual framework remains valid across groups. These findings provide

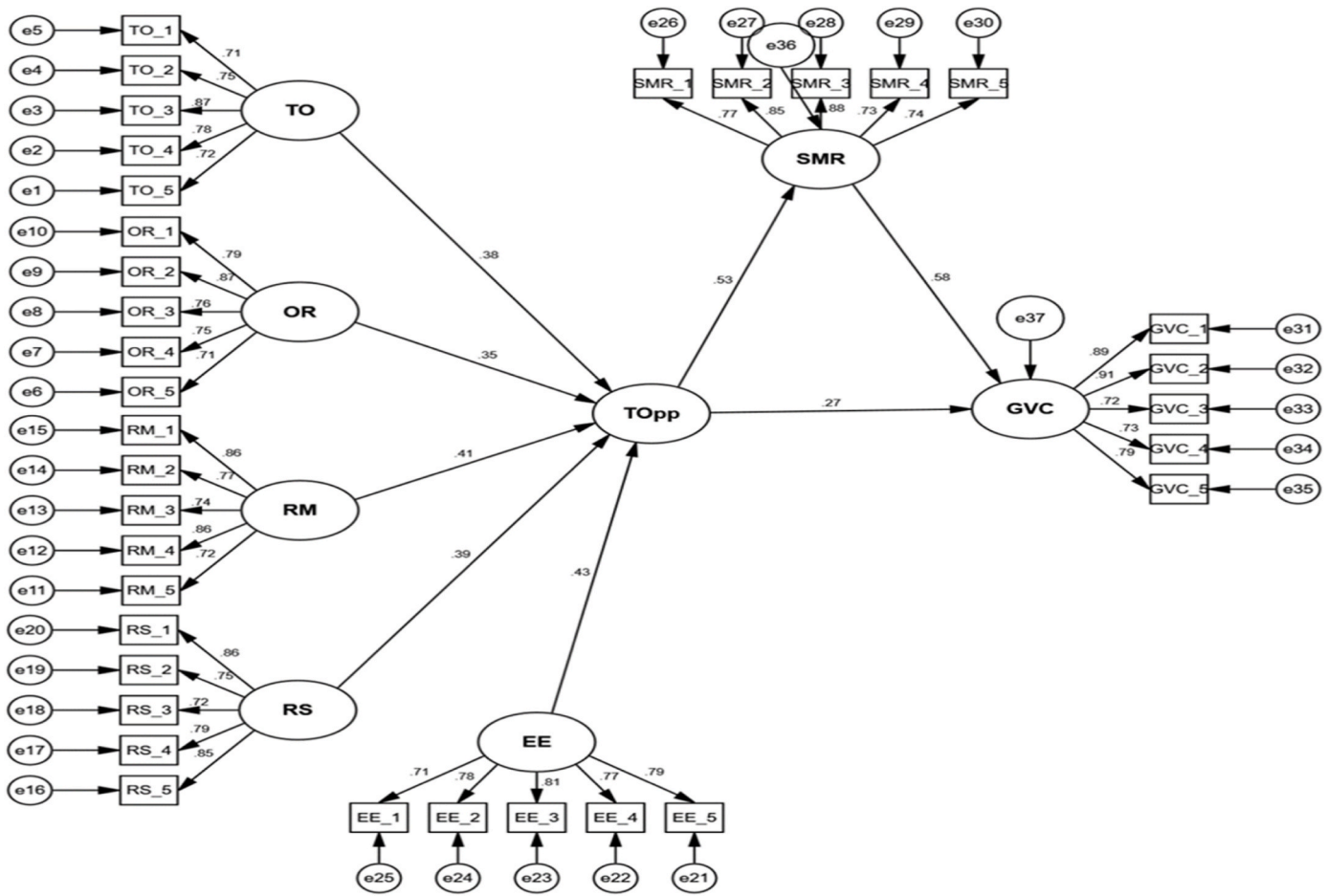


Fig. 3. Overall structural model.

Table 5
Findings of structural model.

Hypothesis	β	z-value	Results
H1: TO → TOpp	.38***	4.791	Accepted
H2: OR → TOpp	.35***	4.508	Accepted
H3: RM → TOpp	.41***	5.116	Accepted
H4: RS → TOpp	.39***	4.963	Accepted
H5: EE → TOpp	.43***	5.455	Accepted
H6: TOpp → GVC	.27***	3.872	Accepted
H7: TOpp → SMR	.53***	6.521	Accepted
H8: SMR → GVC	.58***	6.954	Accepted

Table 6
Assessment of mediating effect.

Hypothesis	Effect	Result
H9: TOpp → SMR → GVC	Path 1 (TOpp → SMR): $\beta = .56$ *** z-value = 6.952 Path 2 (SMR → GVC): $\beta = .61$ *** z-value = 7.687	Accepted (complementary mediation)

Table 7
Invariance tests across men and women.

Model comparison	CMIN diff	p-values
Measurement weights vs Unconstrained	73.51	.000
Structural weights vs Measurement weights	51.18	.002
Structural covariance vs Structural weights	3.96	.092

empirical validation for the integration of gender and emphasize the importance of tailored policy and support mechanisms to address the unique barriers faced by female technopreneurs in the green hydrogen economy.

To explore the gender-based differences in the hypothesized relationships within the conceptual model of technopreneurial opportunities and green-tech venture creation, a comparative analysis of two structural models—one for male technopreneurs (Fig. 4) and one for female technopreneurs (Fig. 5)—was conducted. This comparison aimed to identify significant disparities in the structural path coefficients and was grounded in the methodological guidance of Klesel et al. (2019), who emphasized the use of critical ratio (CR) analysis to assess the statistical significance of differences in path estimates across models. These comparative results, underscore important gender-based variations in how key constructs operate within the green hydrogen technopreneurial landscape in Malaysia.

As presented in Table 8, the study employed Z-value comparisons to further examine the significance of path coefficient differences between the two structural models—one representing male technopreneurs and the other female technopreneurs—within the green hydrogen economy. This approach was used to complement the earlier multi-group SEM analysis, focusing specifically on identifying whether the strength of hypothesized relationships varies significantly between genders. The findings from the Z-value analysis confirm that empirical disparities exist between male and female technopreneurs, reinforcing the hypothesis that constructs function differently across the two groups.

The findings of this study support for Hypothesis 10 (H10), which revealed distinct gender-based variations in technopreneurial behaviour and outcomes, particularly in how male and female entrepreneurs

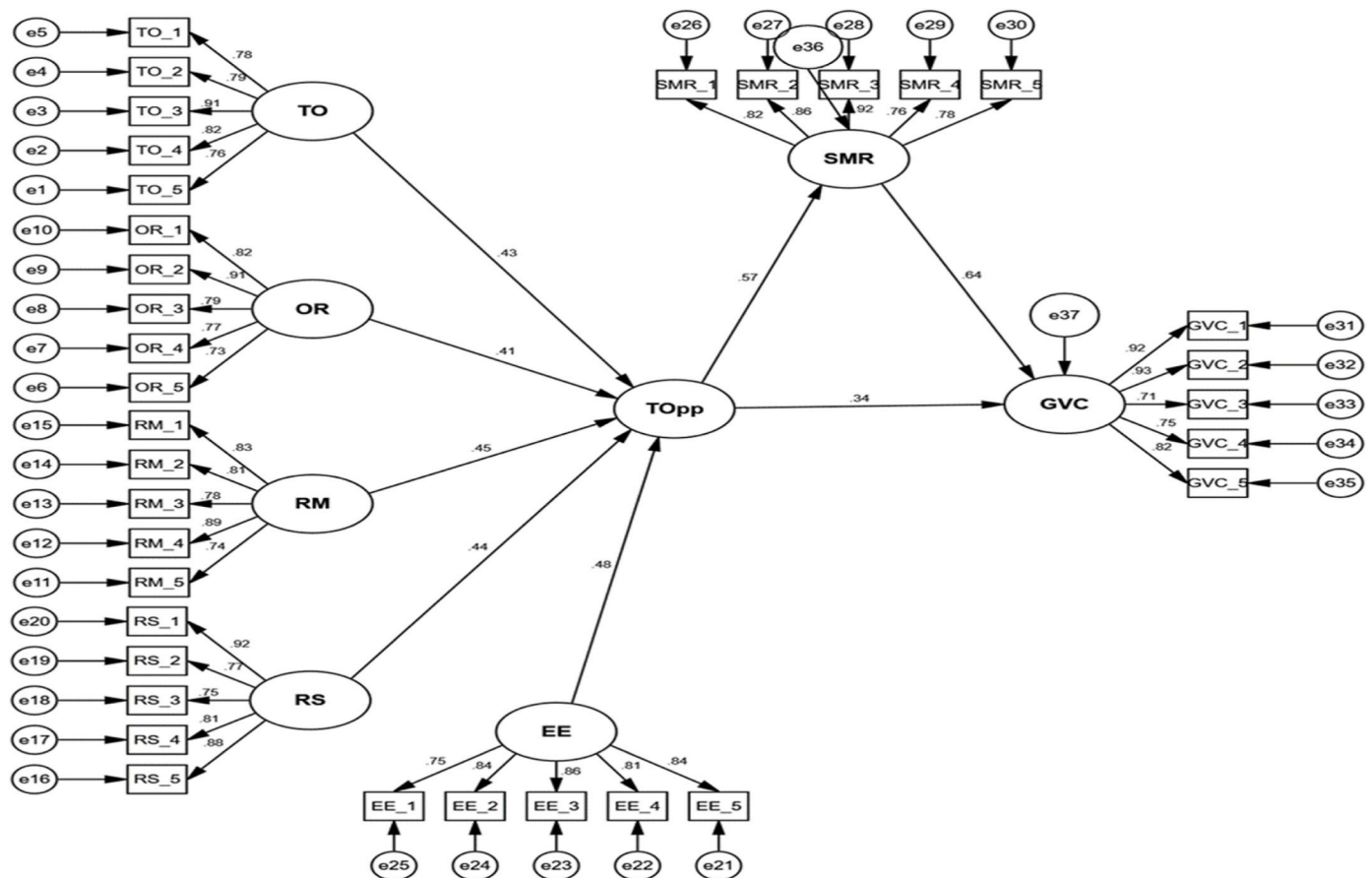


Fig. 4. Structural model for male technopreneurs.

perceive and act upon opportunities in Malaysia's green hydrogen economy. For male technopreneurs, the path coefficients (e.g., TO → Topp: $\beta = .43$; OR → Topp: $\beta = .41$; RM → Topp: $\beta = .45$) demonstrate moderate to strong effects, meaning that a one standard deviation increase in entrepreneurial orientation, opportunity recognition, or resource mobilization translates into a 40–45% rise in access to viable opportunities. By contrast, the coefficients for female technopreneurs are consistently lower (e.g., TO → Topp: $\beta = .37$; OR → Topp: $\beta = .38$; RM → Topp: $\beta = .40$), suggesting that while women also benefit positively, their gains amount to around 36–40%. These differences imply that systemic barriers—such as limited access to financing, professional networks, or regulatory visibility—may constrain women's ability to fully translate entrepreneurial intent into actionable opportunities.

The divergence is even more evident at the outcome stage. Male entrepreneurs show stronger effects in converting opportunities into ventures (Topp → GVC: $\beta = .34$ vs. .29 for women) and in capitalizing on supportive market conditions (SMR → GVC: $\beta = .64$ vs. .56 for women). In real-world terms, this indicates that although both genders are active in the green hydrogen domain, men are more effective in leveraging entrepreneurial traits and market readiness into actual venture creation. Female technopreneurs, despite making significant contributions, remain disadvantaged by structural challenges that dampen the impact of their efforts. These insights underscore the importance of targeted policies and ecosystem-level interventions to ensure that Malaysia's rapidly evolving green hydrogen sector fosters more equitable participation and outcomes across genders.

5. Discussion

The overall findings of this study provide robust empirical support for the proposed conceptual model, demonstrating how various

entrepreneurial and systemic factors influence technopreneurial opportunities and drive green-tech venture creation within Malaysia's evolving green hydrogen economy. The results underscore the critical importance of technopreneurial drivers in shaping green-tech outcomes, while also emphasizing the pivotal role of SMR in enhancing the environmental impact and viability of these ventures. Collectively, these insights offer a comprehensive understanding of how entrepreneurial intent, institutional enablers, and market readiness converge to support green-tech initiatives aligned with broader sustainability objectives. Additionally, the study reveals notable gender disparities, with male technopreneurs exhibiting stronger access to and utilization of technopreneurial opportunities compared to their female counterparts.

5.1. From technopreneurial opportunities to green-tech venture creation

This section synthesizes the discussion of six interrelated hypotheses that collectively explain how technopreneurial opportunities are formed and translated into green-tech venture creation within the green hydrogen economy.

The findings provide strong support for Hypothesis 1 (H1), which posited that technopreneurial orientation is positively associated with technopreneurial opportunities in the green hydrogen economy. This relationship confirms the theoretical linkage between entrepreneurial orientation and the ability to recognize and act upon emerging opportunities in technologically dynamic and environmentally significant sectors. In the context of green hydrogen, which remains a rapidly evolving and capital-intensive field, technopreneurs with a high orientation are more likely to explore and exploit niche areas such as green hydrogen production technologies, sustainable storage solutions, and applications in transportation and industry. These individuals are also more attuned to shifts in consumer preferences, regulatory landscapes,

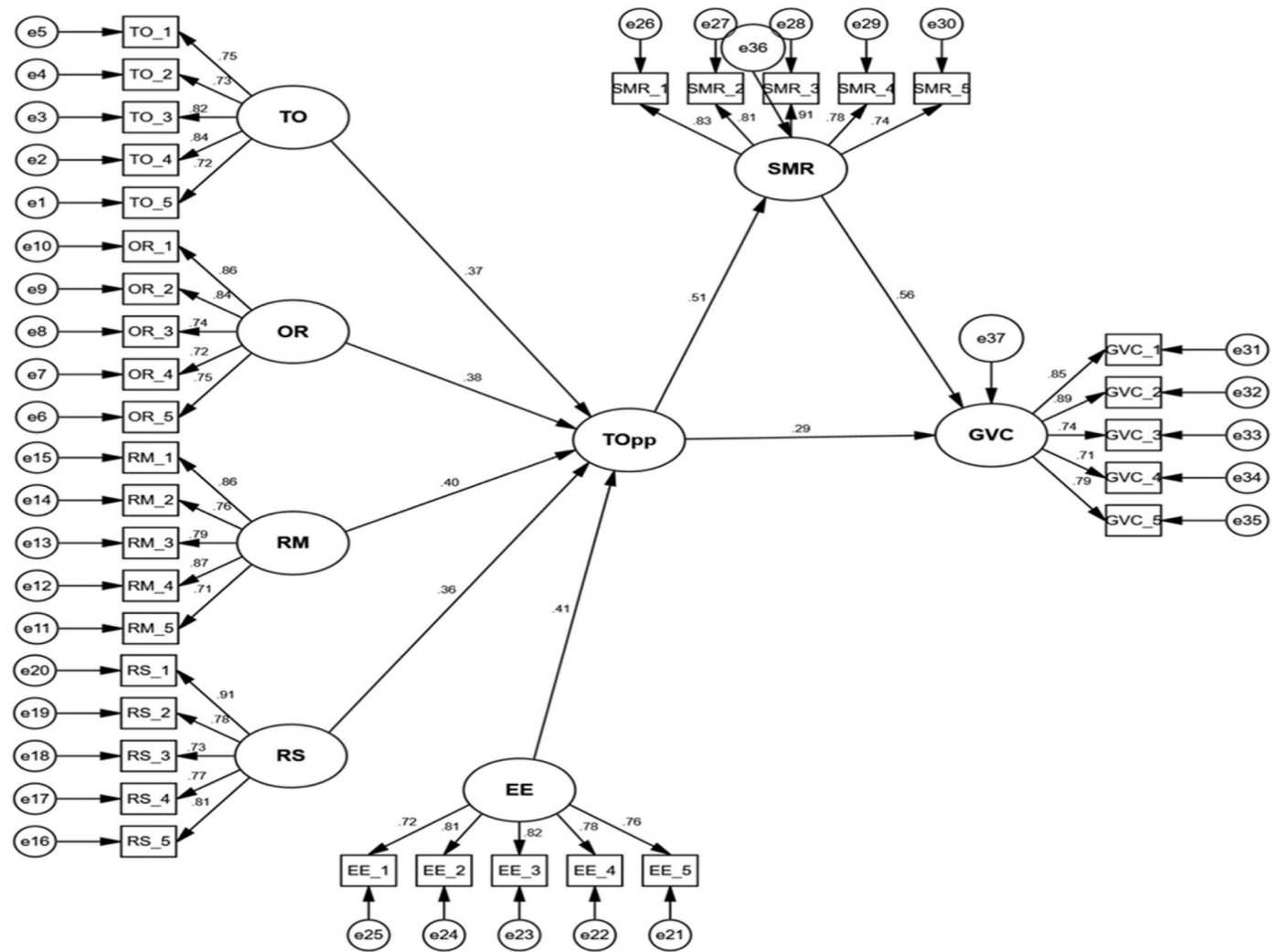


Fig. 5. Structural model for female technopreneurs.

Table 8

Two-by-two analysis.

Hypothesis	Male technopreneurs			Female technopreneurs		
	β	z-value	p-value	β	z-value	p-value
H1: TO → Topp	.43	5.632	.000	.37	4.566	.000
H2: OR → Topp	.41	5.287	.000	.38	4.691	.000
H3: RM → Topp	.45	5.945	.000	.40	5.185	.000
H4: RS → Topp	.44	5.708	.000	.36	4.408	.000
H5: EE → Topp	.48	6.371	.000	.41	5.342	.000
H6: Topp → GVC	.34	4.594	.000	.29	3.976	.001
H7: Topp → SMR	.57	7.116	.000	.51	6.653	.000
H8: SMR → GVC	.64	7.837	.000	.56	7.094	.000

and technological innovations, enabling them to spot market gaps and emerging needs early. This finding aligns with prior studies (such as, Audretsch et al., 2023; Kahpi et al., 2024) which suggest that technopreneurs with a proactive and innovation-driven mindset are more capable of generating new ideas and creating value in uncertain environments. Moreover, Fallah and Soori (2023) shows that women entrepreneurs, although often highly motivated by sustainability goals, face systemic barriers to get the opportunities in green sectors. In Malaysia's context, encouraging women's participation in green hydrogen ventures can help broaden the pool of innovators, making the sector more inclusive and aligned with national sustainability and gender equity goals.

The findings of this study strongly support Hypothesis 2 (H2), which posited a positive association between opportunity recognition and technopreneurial opportunities. This result reinforces the notion that a technopreneur's ability to identify and capitalize on emerging opportunities plays a vital role in advancing green innovation and entrepreneurship. Opportunity recognition, a foundational component of entrepreneurial behaviour, refers to the capacity of individuals to perceive gaps in the market, understand technological shifts, and align them with emerging sustainability trends—such as those represented by green hydrogen technologies. In the current study, respondents who demonstrated a higher level of opportunity recognition were more likely to report access to viable technopreneurial opportunities. This is consistent with prior literature, which emphasizes that entrepreneurs who are attuned to environmental changes and market demands are better equipped to identify areas for value creation and innovation (DiVito & Ingen-Housz, 2021; H  llerstrand et al., 2023). Furthermore, gender-focused study of Veiga et al. (2025) highlights that women entrepreneurs often excel in recognizing sustainability-oriented opportunities, yet remain underrepresented in green technology sectors. In the context of the green hydrogen economy, where technological advancements and environmental policies are rapidly evolving, the ability to recognize and act upon opportunities is especially critical. The study's findings suggest that those who are proactive and perceptive in recognizing green hydrogen-related opportunities are well-positioned to translate these into business ventures, contributing to the broader

objectives of decarbonization and sustainability.

The findings provide compelling support for Hypothesis 3 (H3), which posited that resource mobilization is positively associated with technopreneurial opportunities within the green hydrogen economy. Empirical results affirm that the ability of technopreneurs to effectively mobilize and leverage critical resources—such as financial capital, human expertise, technological infrastructure, and informational networks—significantly enhances their capacity to identify and pursue viable entrepreneurial ventures in the green-tech space. This relationship underscores the foundational role that resource accessibility plays in shaping entrepreneurial activity, particularly in high-tech and sustainability-driven sectors like green hydrogen. Given the resource-intensive nature of green-tech innovation, especially in areas requiring advanced R&D, pilot testing, and regulatory compliance, the ability to secure and allocate resources efficiently becomes a key enabler of opportunity identification and exploitation. Moreover, the positive link between resource mobilization and technopreneurial opportunities suggests that ecosystems supporting green hydrogen entrepreneurship must focus not only on developing innovative ideas but also on ensuring equitable access to necessary inputs. These findings are in line with previous research (such as, [Kowalska-Styczeń et al., 2023](#); [Suganya et al., 2025](#)) emphasizing that successful green entrepreneurship hinges not only on visionary thinking but also on practical capabilities to transform ideas into market-ready solutions.

The findings of this study offer compelling evidence in support of Hypothesis 4 (H4), which posited that regulatory support is positively associated with technopreneurial opportunities in the green hydrogen economy. The empirical results confirm that a supportive regulatory environment plays a significant role in fostering the development and recognition of technopreneurial opportunities, especially within emerging and sustainability-driven industries such as green hydrogen. This outcome aligns well with prior literature (such as [Yi, 2021](#); [Sendra-Pons et al., 2022](#)), that emphasizes the critical role of institutional frameworks in shaping entrepreneurial behaviour. According to Institutional Theory, regulatory institutions—comprising laws, policies, incentives, and government initiatives—establish the formal rules that either enable or constrain entrepreneurial activity. When governments actively support green innovation through targeted policies, subsidies, grants, and regulatory clarity, they reduce uncertainty and risk for entrepreneurs, thereby encouraging technopreneurial engagement in sustainable ventures. In the context of Malaysia's green hydrogen economy, regulatory support can include measures such as tax incentives for clean energy start-ups, streamlined licensing procedures, investment in green infrastructure, and strategic roadmaps aligned with national decarbonization goals. These initiatives not only reduce entry barriers but also legitimize green ventures in the eyes of investors, consumers, and other stakeholders, increasing their chances of success.

The results provide robust empirical support for Hypothesis 5 (H5), which posited that a supportive entrepreneurial ecosystem is positively associated with technopreneurial opportunities in the green hydrogen economy. This result underscores the importance of a well-developed and enabling entrepreneurial environment in fostering opportunity identification, innovation, and new venture creation within the green hydrogen sector. This study's findings resonate with the work of [Qoriawan and Apriliyanti \(2023\)](#), who emphasized that vibrant entrepreneurial ecosystems are characterized by dense social networks, institutional support, and innovation infrastructure that foster entrepreneurial discovery and growth. Similarly, [Schmutzler et al. \(2021\)](#) argued that regions with strong entrepreneurial ecosystems experience higher rates of opportunity-driven entrepreneurship due to the presence of enabling conditions and supportive actors. Within Malaysia's green hydrogen economy, a supportive entrepreneurial ecosystem might include initiatives such as university-led research and development programs, public-private innovation hubs, specialized funding mechanisms for clean energy start-ups, and active engagement of industry stakeholders in policymaking. These elements not only facilitate the

emergence of technopreneurial opportunities but also enhance the ability of entrepreneurs to mobilize resources and commercialize green innovations. Furthermore, this positive association highlights that the entrepreneurial ecosystem does not operate in isolation but interacts with other constructs—such as technopreneurial orientation and regulatory support—to reinforce opportunity development. In other words, the strength and coherence of the ecosystem can amplify or inhibit the translation of individual entrepreneurial traits into actionable opportunities, especially in high-technology and high-risk domains like green hydrogen.

The findings of this study provide compelling support for Hypothesis 6 (H6), which posited that technopreneurial opportunities are positively associated with green-tech venture creation in the green hydrogen economy. The empirical results strongly affirm this relationship, highlighting that the identification, accessibility, and exploitation of technopreneurial opportunities are pivotal to the formation and development of green-tech ventures, particularly within the emerging and innovation-intensive green hydrogen sector. This finding aligns with prior research by [Kuckertz et al. \(2017\)](#), who emphasized that opportunity recognition and exploitation are foundational to the entrepreneurial process. Particularly in sectors driven by technological innovation, the ability to identify opportunities based on emerging science and evolving market needs is often what differentiates successful ventures from those that fail to gain traction. Additionally, this result resonates with the Resource-Based View (RBV), which suggests that strategic resources such as knowledge, innovation, and networks—often embedded in technopreneurial opportunities—can provide competitive advantage when they are rare, valuable, and difficult to imitate. Entrepreneurs operating within a supportive ecosystem and regulatory environment are better positioned to harness these opportunities, transforming them into green-tech start-ups that address energy transition and sustainability goals. In the Malaysian green hydrogen economy, this association underscores the importance of facilitating access to opportunity-rich environments for potential technopreneurs. Such access might include increased investment in R&D, the establishment of technology parks and incubators, government-backed innovation grants, and greater industry-academia collaboration—all of which can help translate abstract opportunities into tangible ventures.

5.2. The mediating role of market readiness in venture development

This section integrates the discussion of three interrelated hypotheses that explain the role of SMR in shaping green-tech venture creation within the green hydrogen economy.

The study offers strong empirical support for Hypothesis 7 (H7), which posited that technopreneurial opportunities are positively associated with SMR in the green hydrogen economy. The results affirm that as technopreneurs identify and leverage emerging opportunities—particularly those grounded in technological innovation and environmental sustainability—market readiness improves in tandem, enhancing the potential for successful commercialization of green hydrogen ventures. This finding aligns with prior research suggesting that entrepreneurial activity, especially in emerging sectors, plays a critical role in shaping market dynamics. For instance, scholars such as [Brege and Kindström \(2021\)](#) and [Tolossa et al. \(2024\)](#) have highlighted the proactive role of entrepreneurs in not just responding to market conditions but actively creating new markets through innovation and strategic action. In the context of green hydrogen, this implies that technopreneurs who seize opportunities can help reduce market uncertainty, encourage investment, and accelerate the development of necessary infrastructure. Furthermore, the positive association between technopreneurial opportunities and SMR supports the theoretical underpinnings of the Resource-Based View (RBV) and Institutional Theory. From the RBV perspective, opportunity-driven actions are seen as strategic capabilities that can enhance a firm's market positioning. From the Institutional Theory perspective, such actions help shape norms,

practices, and policy responses, all of which contribute to a more conducive and stable market environment for green hydrogen technologies.

The findings provide strong empirical support for Hypothesis 8 (H8), which posited that SMR is positively associated with green-tech venture creation in the green hydrogen economy. The results affirm the pivotal role of a well-prepared and supportive market in enabling the successful development and implementation of green technological ventures. This finding aligns with previous literature highlighting the importance of market readiness in innovation adoption and entrepreneurial success. For instance, [Palm \(2022\)](#) emphasized that innovation diffusion in emerging sectors is greatly facilitated by the maturity of the market environment. Similarly, [Ciumasu \(2023\)](#) noted that even well-conceived technological innovations struggle to gain traction without corresponding readiness within the market. In Malaysia's green hydrogen economy, where the technology and its supporting infrastructure are still developing, the significance of SMR cannot be overstated. A market that is ready—through the presence of green policies, public-private partnerships, technical standards, and end-user education—reduces uncertainty and risk for technopreneurs. It enhances confidence in return on investment, stimulates demand, and facilitates stakeholder engagement, all of which are essential for green-tech venture success.

The findings of this study provide compelling support for Hypothesis 9 (H9), which proposed that SMR mediates the relationship between technopreneurial opportunities and green-tech venture creation in the green hydrogen economy. The empirical results confirmed this mediating effect through a complementary mediation model, where both the direct and indirect pathways were statistically significant and positively related. The confirmation of SMR as a mediator emphasizes the importance of a systems-level perspective on entrepreneurship in the green hydrogen sector. It suggests that technopreneurial activity is embedded within a broader ecosystem, where institutional and market-level conditions significantly influence entrepreneurial outcomes. This is particularly relevant in emerging economies like Malaysia, where green hydrogen infrastructure and market maturity are still developing. This finding also aligns with prior research emphasizing the critical role of context in entrepreneurial success. For example, [Kallas and Parts \(2021\)](#) and [Yi \(2021\)](#) noted that the readiness of external conditions plays a decisive role in whether entrepreneurial intentions lead to successful enterprise formation. In green and sustainable ventures, where technology is evolving and often capital-intensive, the readiness of the market becomes even more crucial. Therefore, SMR acts as a strategic bridge between opportunity and execution, enabling the materialization of green-tech ventures from conceptual opportunities.

A deeper explanation of this mechanism highlights that SMR translates recognized opportunities into viable ventures by reducing uncertainty, signalling legitimacy, and creating pathways for financing, partnerships, and adoption. In the Malaysian green hydrogen economy, where policies and infrastructure are still nascent, SMR functions as a gatekeeper: ventures can only scale when the market demonstrates sufficient absorptive capacity. Gender dynamics add an additional layer to this mediating role. Male technopreneurs are better positioned to leverage SMR, converting opportunities into large-scale ventures. By contrast, female technopreneurs, though actively engaged, often rely on community-based or niche applications that do not align seamlessly with mainstream market readiness indicators. As a result, their opportunities may stall at the conceptual or pilot stage unless specific gender-responsive support structures—such as inclusive procurement policies, and technical mentoring—are introduced. This underscores that SMR not only mediates opportunity-to-venture pathways in general but also amplifies existing gender disparities by favouring ventures embedded in dominant industrial and financial networks.

5.3. Gendered pathways in accessing and leveraging opportunities

This section discusses the hypothesis examining gender-based

differences in accessing and leveraging technopreneurial opportunities within the green hydrogen economy. The focus is on understanding how opportunity development and conversion into ventures may vary across male and female technopreneurs, rather than treating gender as a standalone factor.

The findings of this study provide strong support for Hypothesis 10 (H10), which posited that gender disparities exist such that men have greater access to technopreneurial opportunities than women in the context of green-tech venture creation within the green hydrogen economy. The multi-group SEM analysis revealed statistically significant differences in the path coefficients between male and female technopreneurs, confirming that male participants consistently exhibited stronger associations across key constructs—particularly from technopreneurial opportunities to green-tech venture creation. These disparities suggest that male technopreneurs are currently better positioned to leverage existing resources, institutional networks, and market readiness to advance green innovation initiatives.

Several factors may contribute to this imbalance, including traditional gender norms, structural barriers, unequal access to funding, mentorship, and policy support—issues that have been widely documented in entrepreneurship literature across various sectors ([Coronel-Pangol et al., 2024](#); [Kulkarni & Ghosh, 2021](#)). In the specific context of the green hydrogen sector, these structural gaps are heavily amplified by the unique technical and economic characteristics of the industry. Because green hydrogen production, storage, and distribution require immense up-front capital investment and long-term hardware testing, early-stage financing relies heavily on deep tech venture capital and institutional funding. Female technopreneurs face pronounced obstacles here, as clean-energy venture financing remains overwhelmingly male-dominated and reliant on legacy fossil-fuel or utility industry networks. Furthermore, green hydrogen innovations are deeply anchored in specialized STEM domains—such as chemical engineering, advanced electrolysis, and cryogenics—fields in which women face systemic underrepresentation in technical leadership roles within Malaysia. Consequently, male technopreneurs are structurally advantaged; they can navigate and exploit complex public-private partnerships, large-scale energy infrastructure projects, and formal regulatory agencies much more fluidly than their female counterparts, leading to a higher rate of translating basic opportunities into formalized green ventures.

However, the results also highlight an important nuance—while men currently demonstrate stronger outcomes in capitalizing on technopreneurial opportunities, the opportunities for women are not absent but remain under-realized. The data show that female technopreneurs still participate actively in the green economy and exhibit positive responses across most constructs, although at relatively lower intensities than their male counterparts. This suggests that the foundational interest, capability, and intent among women exist, but systemic support mechanisms may not be equally accessible or effective for them. Crucially, while male technopreneurs often drive large-scale, high-capacity commercialization pathways, female technopreneurs show localized agility by focusing on service-oriented or decentralized hydrogen applications, such as localized industrial decarbonization consulting, digital supply chain tracking, and smart grid software integration. These niches require less physical infrastructure but are highly vital for the broader ecosystem. The findings also resonate with broader global efforts to integrate gender equity into sustainability and climate change agendas. As highlighted in UN-SDGs, particularly SDG 5 (Gender Equality) and SDG 13 (Climate Action), promoting women's participation in green innovation is not only a matter of equity but a strategic imperative for achieving comprehensive and inclusive sustainability transitions. Without dismantling the systemic networks that filter women out of large-scale infrastructure projects, Malaysia risks ignoring a critical segment of its clean-tech talent pool, ultimately slowing down the deployment of localized hydrogen solutions.

5.4. Toward an integrated and inclusive view of green technopreneurship

This study moves beyond hypothesis-by-hypothesis interpretation by offering a more integrated explanation of how technopreneurial opportunities are shaped and realized within the green hydrogen economy. The findings suggest that opportunity formation and venture creation are not isolated outcomes but emerge from the interaction of capabilities, institutional conditions, and market readiness. Importantly, this process is not uniform; it is influenced by structural access to networks, resources, and legitimized pathways to commercialization. This integrated perspective advances theory by demonstrating that opportunity development and exploitation are co-evolutionary processes embedded within broader socio-economic systems.

In this context, the findings also extend understanding of gendered participation by highlighting the underexplored innovation potential of women in community-based and decentralized hydrogen applications. Female technopreneurs often engage in localized, service-oriented, and sustainability-driven solutions—such as off-grid energy systems, community energy services, and small-scale hydrogen applications—which contribute meaningfully to inclusive and socially embedded energy transitions. However, these forms of innovation are less aligned with dominant, capital-intensive commercialization pathways and are therefore less visible within formal market structures.

Beyond venture creation, the results indicate that women's participation in the green hydrogen economy extends into broader political, social, and institutional spheres, including advocacy, community engagement, and sustainability-oriented ecosystem development. This suggests that their contribution to sustainable transitions is not limited to firm-level outcomes but also involves shaping norms, practices, and acceptance of green technologies. Recognizing these multidimensional roles expands the current understanding of technopreneurship by incorporating social and institutional value creation alongside economic performance.

6. Conclusion

This study examined the factors shaping technopreneurial opportunities and their role in fostering green-tech venture creation within Malaysia's emerging green hydrogen economy. Drawing on a robust conceptual framework, the findings confirmed that technopreneurial orientation, opportunity recognition, resource mobilization, regulatory support, and the entrepreneurial ecosystem significantly contribute to the formation of technopreneurial opportunities. In turn, these opportunities play a critical role in driving the creation of green-tech ventures, with SMR acting as a key enabling condition that links opportunity development to venture realization. Importantly, the findings demonstrate that this process is institutionally embedded and varies across gendered pathways, highlighting that access to and conversion of opportunities are shaped by structural conditions and ecosystem dynamics. This reinforces the importance of both individual entrepreneurial capabilities and systemic enablers.

The study contributes to the growing body of knowledge on sustainable entrepreneurship by highlighting how multiple drivers collectively facilitate innovation in a high-potential yet underexplored sector. More specifically, it advances understanding by showing that technopreneurial opportunity formation is not only resource- and capability-driven but also conditioned by market readiness and gendered institutional contexts. Its findings provide valuable insights for policymakers, practitioners, and scholars seeking to advance green hydrogen initiatives through entrepreneurial pathways. The following sections present the study's theoretical and practical implications, as well as its limitations and recommendations for future research.

6.1. Theoretical implications

This study offers a more integrated and theoretically novel

contribution by combining the Resource-Based View (RBV), Institutional Theory, and the Gendered Ecosystem Perspective to explain technopreneurial opportunities and green-tech venture creation within the green hydrogen economy. Rather than treating these perspectives independently, the study synthesizes them into a cross-level framework that links internal capabilities, external institutions, and gendered ecosystem dynamics.

From the RBV, the findings extend existing theory by conceptualizing technopreneurial opportunities as higher-order, dynamic capabilities, rather than static resources. Internal capabilities—such as technopreneurial orientation, opportunity recognition, and resource mobilization—are shown to enable opportunity formation and exploitation, reinforcing their role in driving green-tech venture creation. This shifts RBV from a resource-possession logic toward a capability-activation perspective in sustainability-driven contexts.

From an Institutional Theory perspective, the study demonstrates that regulatory support and entrepreneurial ecosystems actively shape and enable opportunity structures, rather than merely influencing outcomes. A key theoretical advancement is the identification of SMR as a bridging mechanism, through which institutional conditions are translated into market-viable ventures. This positions SMR as a system-level construct that operationalizes the link between institutional support and entrepreneurial outcomes.

Through the Gendered Ecosystem Perspective, the study moves beyond identifying disparities to explaining how gender moderates opportunity conversion processes within institutional and market structures. The findings show that while both male and female technopreneurs engage in opportunity recognition, the pathways to venture creation are uneven due to differential access to formal networks, resources, and market-aligned opportunities. This refines the perspective by demonstrating that entrepreneurial ecosystems are structurally gendered in how opportunities are scaled, not merely accessed.

Collectively, the study advances theory in three key ways. First, it integrates RBV and Institutional Theory through the mediating role of SMR, linking resources to outcomes via market conditions. Second, it extends the Gendered Ecosystem Perspective by positioning gender as a contextual moderator of opportunity exploitation. Third, it proposes a multi-stage view of technopreneurship, where opportunity recognition, institutional validation, and market readiness jointly determine venture creation.

6.2. Practical implications

The findings offer focused implications for policymakers, investors, support organizations, and technopreneurs advancing Malaysia's green hydrogen economy. Priority should be given to strengthening opportunity recognition and capability development through targeted, hydrogen-specific training embedded within existing national programs (e.g., SME Corp, Cradle Fund, MaGIC). These initiatives should emphasize market understanding, technology literacy, and commercialization pathways. To improve resource mobilization, financial institutions and public schemes (e.g., Bank Pembangunan Malaysia, GTFS) can consider developing more flexible and risk-sharing financing mechanisms tailored to early-stage green ventures. In particular, gender-sensitive financing schemes, such as dedicated funding windows or co-financing support for women-led green-tech ventures, can help address structural access gaps. In parallel, incremental regulatory support, such as clearer guidelines, streamlined licensing, and selective incentives aligned with NETR and HETR, can help reduce uncertainty and support venture development.

The study also highlights the importance of ecosystem coordination and market readiness (SMR) in enabling venture success. Universities, incubators, and public agencies could strengthen collaboration by supporting pilot projects, mentorship, and access to testing infrastructure, particularly in emerging hubs such as Sarawak. Additionally, the introduction of technical certification and training programs tailored to

green hydrogen technologies can enhance capability development and improve participation across diverse groups. At the market level, gradual investments in awareness-building and supply chain readiness can support adoption without overstating immediate demand potential. Finally, addressing gender gaps requires practical and scalable measures, including improving access to financing, expanding mentorship and industry linkages, and ensuring inclusive participation in innovation programs, rather than relying solely on broad policy mandates. Collectively, these targeted actions can support a more inclusive and effective transition toward a sustainable green hydrogen ecosystem.

6.3. Limitations and recommendations

This study provides important insights into the drivers of technopreneurial opportunities and green-tech venture creation in Malaysia's emerging hydrogen economy, but several limitations must be acknowledged. First, the reliance on cross-sectional survey data introduces inherent constraints, as the findings reflect relationships at a single point in time and cannot capture causal dynamics or changes over the course of entrepreneurial development. Future research should adopt longitudinal designs to trace how technopreneurial orientation, resource mobilization, and market readiness evolve in response to policy reforms, technological advancements, and shifting market conditions.

Second, the use of self-reported survey responses may be subject to perceptual bias, including social desirability effects and common method variance. Although statistical checks were undertaken to minimize these risks, future studies could benefit from a mixed-methods approach, integrating interviews, case studies, or archival data to triangulate findings and strengthen validity. Similarly, experimental or behavioural methods could be employed to capture actual decision-making processes rather than relying solely on self-reported perceptions.

Third, sampling bias presents another limitation. The study focused exclusively on technopreneurs in Malaysia, a country with unique institutional, cultural, and policy contexts. While this enhances local policy relevance, it limits generalizability to other economies. Comparative studies across ASEAN countries or other hydrogen-developing economies could test whether the relationships observed here hold across different institutional environments. Moreover, as the sample was accessed through networks, associations, and incubators, entrepreneurs outside these formal systems may have been underrepresented. Broader sampling frames and probability-based approaches could help overcome this limitation.

Finally, potential endogeneity issues in Structural Equation Modeling (SEM)—such as reciprocal causality between constructs—were not fully addressed. Future research could apply longitudinal SEM, instrumental variable techniques, or panel data approaches to mitigate endogeneity concerns and provide more robust causal inferences. In addition, extending the framework to include

overlooked factors such as digital infrastructure, innovation capabilities, or environmental values would allow for a more holistic understanding of the conditions that foster green-tech venture creation.

Consent to participate

Written informed consent was obtained from all respondents before participation. All methods were carried out in accordance with relevant guidelines and regulations of studies involving human participants.

Ethics approval

This study was reviewed and approved by Universiti Malaysia Sarawak Ethics Committee with the approval number: UNIMAS-FEB-11/2024/R03.

Data availability statement

Data available on request due to privacy restrictions.

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CRediT authorship contribution statement

Muhammad Farhan Jalil: Formal analysis, Investigation, Methodology, Writing – original draft. **Kartinah Ayupp:** Conceptualization, Software, Writing – review & editing. **Abu Hassan Bin Md Isa:** Project administration, Software, Supervision. **Dayang Affizzah Binti Awang Marikan:** Funding acquisition, Validation.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Measurement items (English version)

Variables	Items	Measurement Path
Technopreneurial orientation	TO_1	I am inclined to adopt new green technologies before others.
	TO_2	I prefer launching ventures that use emerging green technologies.
	TO_3	I often identify trends in green technology for business purposes.
	TO_4	I actively seek technological solutions to address environmental challenges.
	TO_5	I set clear goals to build technology-driven sustainable businesses.
Opportunity recognition	OR_1	I can identify unmet market needs in the green hydrogen economy.
	OR_2	I frequently discover new ideas for sustainable businesses.
	OR_3	I recognize how green hydrogen can solve current energy problems
	OR_4	I am confident in identifying viable green-tech ventures.
	OR_5	I evaluate societal challenges as potential business opportunities.
Resource mobilization	RM_1	I can secure financial resources to support green-tech startups.
	RM_2	I have access to technical knowledge relevant to green hydrogen.
	RM_3	I can mobilize a skilled team to pursue green ventures.

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Variables	Items	Measurement Path
Regulatory support	RM_4	I can acquire infrastructure or technology for a green venture.
	RM_5	I know how to leverage networks to obtain needed resources.
	RS_1	There are clear policies for starting a green-tech business.
	RS_2	Regulatory bodies are accessible for green-tech business inquiries.
	RS_3	Financial incentives are available for green hydrogen entrepreneurs.
Entrepreneurial ecosystem	RS_4	The licensing process for green-tech ventures is straightforward.
	RS_5	Regulatory frameworks promote women's participation in green ventures.
	EE_1	There is collaboration between industry and academia in green hydrogen.
	EE_2	There is a strong network of green hydrogen entrepreneurs.
	EE_3	Investors are interested in funding green-tech innovations.
Sustainable market readiness	EE_4	Events and forums promote green-technopreneurial development.
	EE_5	Mentorship and guidance are accessible for green entrepreneurs.
	SMR_1	The market is ready to adopt green hydrogen solutions.
	SMR_2	Customers are increasingly aware of green hydrogen benefits.
	SMR_3	There is a growing demand for sustainable energy products.
Green-tech venture creation	SMR_4	Stakeholders are responsive to green-tech innovations.
	SMR_5	Institutions promote awareness of green hydrogen solutions.
	GVC_1	I have initiated a venture based on green hydrogen technology.
	GVC_2	I am in the process of starting a green-tech enterprise.
	GVC_3	I have identified a viable business model for green hydrogen.
	GVC_4	My venture aims to reduce carbon emissions using new tech.
	GVC_5	My business incorporates sustainability as a core strategy.

Appendix B. Item Pengukuran (Bahasa Malaysia version)

Variables	Items	Measurement Path
Orientasi Teknousahawan	TO_1	Saya cenderung untuk mengguna pakai teknologi hijau baharu sebelum orang lain.
	TO_2	Saya lebih suka melancarkan perniagaan yang menggunakan teknologi hijau yang sedang muncul.
	TO_3	Saya sering mengenal pasti trend dalam teknologi hijau untuk tujuan perniagaan.
	TO_4	Saya secara aktif mencari penyelesaian teknologi untuk menangani cabaran alam sekitar.
	TO_5	Saya menetapkan matlamat yang jelas untuk membina perniagaan lestari berasaskan teknologi.
Pengenalpastian Peluang	OR_1	Saya dapat mengenal pasti keperluan pasaran yang belum dipenuhi dalam ekonomi hidrogen hijau.
	OR_2	Saya kerap menemui idea baharu untuk perniagaan yang lestari.
	OR_3	Saya mengenal pasti bagaimana hidrogen hijau boleh menyelesaikan masalah tenaga semasa.
	OR_4	Saya yakin dalam mengenal pasti perniagaan teknologi hijau yang berdaya maju.
	OR_5	Saya menilai cabaran masyarakat sebagai peluang perniagaan yang berpotensi.
Mobilisasi Sumber	RM_1	Saya boleh mendapatkan sumber kewangan untuk menyokong perusahaan teknologi hijau.
	RM_2	Saya mempunyai akses kepada pengetahuan teknikal yang berkaitan dengan hidrogen hijau.
	RM_3	Saya boleh menggerakkan pasukan yang mahir untuk menjalankan perusahaan hijau.
	RM_4	Saya boleh memperoleh infrastruktur atau teknologi untuk perusahaan hijau.
	RM_5	Saya tahu bagaimana memanfaatkan rangkaian untuk mendapatkan sumber yang diperlukan.
Sokongan Peraturan	RS_1	Terdapat dasar yang jelas untuk memulakan perniagaan teknologi hijau.
	RS_2	Badan pengawalseliaan mudah dihubungi untuk pertanyaan berkaitan perniagaan teknologi hijau.
	RS_3	Insentif kewangan disediakan untuk usahawan hidrogen hijau.
	RS_4	Proses pelesenan bagi perusahaan teknologi hijau adalah mudah dan jelas.
	RS_5	Rangka kerja peraturan menggalakkan penyertaan wanita dalam perusahaan hijau.
Ekosistem Keusahawanan	EE_1	Terdapat kerjasama antara industri dan akademik dalam bidang hidrogen hijau.
	EE_2	Terdapat rangkaian usahawan hidrogen hijau yang kukuh.
	EE_3	Pelabur berminat untuk membiayai inovasi teknologi hijau.
	EE_4	Acara dan forum mempromosikan pembangunan teknousahawan hijau.
	EE_5	Mentoran dan bimbingan mudah diakses untuk usahawan hijau.
Kesiapsiagaan Pasaran Lestari	SMR_1	Pasaran bersedia untuk menerima pakai penyelesaian hidrogen hijau.
	SMR_2	Pelanggan semakin sedar tentang manfaat hidrogen hijau.
	SMR_3	Terdapat peningkatan permintaan terhadap produk tenaga lestari.
	SMR_4	Pemegang taruh memberi respons terhadap inovasi teknologi hijau.
	SMR_5	Institusi mempromosikan kesedaran tentang penyelesaian hidrogen hijau.
Penciptaan Perusahaan Teknologi Hijau	GVC_1	Saya telah memulakan sebuah perusahaan berasaskan teknologi hidrogen hijau.
	GVC_2	Saya sedang dalam proses memulakan perusahaan teknologi hijau.
	GVC_3	Saya telah mengenal pasti model perniagaan yang berdaya maju untuk hidrogen hijau.
	GVC_4	Perusahaan saya bertujuan untuk mengurangkan pelepasan karbon menggunakan teknologi baharu.
	GVC_5	Perniagaan saya menggabungkan kelestarian sebagai strategi teras.

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