How Industry 4.0 technologies and open innovation can improve green innovation performance?

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Abstract

Purpose – This study investigates the impact of Industry 4.0 technologies on green innovation performance. In this relationship, the mediating role of green innovation behavior is also studied. Moreover, open innovation is tested as a mediator between Industry 4.0 technologies and green innovation behavior.

Design/methodology/approach – A quantitative research method is adopted in which a structured questionnaire was used to collect data from 217 manufacturing firms of Malaysia. After collecting data, the partial least squares-structural equation modeling (PLS-SEM) technique is applied to analyze data and test the hypothesis of study.

Findings – It is found that Industry 4.0 positively impacts open innovation which leads to green innovation behavior. Also, the former lays positive impact on green innovation behavior which leads to improve green innovation performance.

Research limitations/implications – The authors conclude that Industry 4.0 technologies can play an important role to improve green innovation performance of Malaysian manufacturing firms by managing open innovation for green innovation behavior which further improves the green innovation performance. In this context, it is recommended that strategists and policymakers should undertake the role of open innovation and Industry 4.0 technologies to promote environment-friendly innovations and to promote the green behavior in companies. The authors suggest hereby that firms should be given incentives to adopt and utilize Industry 4.0 technologies and collaborative innovation interactions – as they foster a climate for sustainable green innovations (which is also a key component to achieve competitive advantage) and a growing concern nowadays.

Practical implications – First of all the research contributes to achieving the broader of United Nations to promote sustainable innovation through green innovations. Moreover, the companies can also incorporate the findings and insights of this study while devising their policies to foster green innovations.

Originality/value – This research has done the novel contribution by bridging the gap between open innovation approach and sustainability fields while promoting green innovations in small and medium enterprises (SMEs). These two research fields are rarely studied in previous studies by focusing open innovation particularly. Hence, the authors suggest researchers to undertake these fields to further

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enhance the level of scholarship between innovation management and sustainability. Also, the authors recommend considering technological orientation and technological absorptive capacity of firms to improve green innovations. The current study has investigated the SMEs perspective in general irrespective to their sectoral differences, thus, for future researchers the authors suggest investigating the sector-wise comparison, i.e. electrical and electronics sector, chemical sector, etc.; or service and manufacturing sector differences.

Keywords Industry 4.0, Open innovation, Green innovation performance, SMEs, PLS-SEM

Paper type Research paper

1. Introduction

Driven by the technologies of Fourth Industrial Revolution, manufacturing concerns across the globe are seriously focusing on the environmental agenda. As a result, the inclusion and development of technologies that prevent or reduce pollution in production processes are increasingly becoming an essential condition for survival. In this vein, green innovation is in the limelight of both businesses and policymakers to cope with the rising economic and environmental pressures (Tang *et al.*, 2020). The priorities of manufacturers are switched from efficient production toward developing environmentally friendly material and reducing pollutants in production processes (Ma *et al.*, 2018). Nevertheless, they have started to perceive themselves as the organizations that genuinely fulfill society's needs. As this perception prevails, the societal expectations from manufacturing firms for improving the environmental condition and life quality within the society are also increased. Nevertheless, policy support for the firms to perform environment-friendly innovations is provided which leads toward sustainable growth. Such innovations are pronounced as green innovations as well which are seen as "*a product, production process, service or management or business method that is novel to (them) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives*" (Kemp and Pontoglio, 2007, p. 10). It is also considered as an introduction or implementation of a new or radically improved product, services, organizational procedures and processes to increase contribution toward the environment. Traditional examples of this notion include the reduction of raw material and energy use per unit of production output; an improved recycling method for products after their use; and, reduction of carbon footprint and air, noise, water and soil pollution (Kemp and Pontoglio, 2007; Horbach *et al.*, 2012; Rehfeld *et al.*, 2007; Li *et al.*, 2019). To fulfill these objectives, firms are using Industry 4.0 technologies which are lessening environmental concerns by reducing unnecessary operations such as paperless mechanisms and improved manufacturing processes through robotics, Internet of things (IoT) and advanced cyber-physical systems (CPSs) including many others (Mubarak and Petraite, 2020). The concept of green innovation is categorized as green product innovation and green process innovation (GPI) (Chen *et al.*, 2006). While studying green innovation, previous research has focused on its antecedents and outcomes by concentrating on innovative technologies to gauge their impact on financial performance. However, measuring their performance through green innovation is rarely considered (Cheng *et al.*, 2014).

Supporting green innovation is a challenging job due to the specific characteristics associated with standardized innovations (Horbach *et al.*, 2012). Thereby, firms are required to go beyond their existing industrial knowledge base to explore new sources of knowledge – internally or externally – to overcome the confined sandbox of standards. However, firms and especially SMEs cannot rely solely on their resources to generate knowledge (research and development (R&D)). Consequently, they collaborate and cooperate with their rival firms and external partners whereby they use the knowledge, expertise and assets of each other – as per the notion of open innovation (Chesbrough, 2006; De Marchi and Grandinetti, 2013; De Marchi, 2012). In the case of environmental-related green innovations, firms are increasingly relying on open innovation approach where their internal and external knowledge borders become permeable (Chesbrough, 2003, 2006). The degree to which green

innovations can be improved through open innovation mode is a key policy debate – to mitigate environmental issues. In this connection, government authorities are required to intervene for eliminating the obstacles that hinder the green effect of openness of innovation. Such obstacles can lead to systematic failure in innovations (Metcalfe, 1995) which can be avoided through green innovation behavior that firms should adopt while doing interactions with outside partners to enhance their knowledge base (and R&D) on green innovation (Georghiou and Clarysse, 2006; Tang *et al.*, 2020).

Although, the influence of open innovation in the context of technological innovations, innovation investments, innovation appropriability and innovation diffusion is studied (Laursen and Salter, 2006; Henkel, 2006). However, its role to improve green innovation behavior for green innovation performance is not yet thoroughly studied. Therefore, this paper studies the impact of Industry 4.0 technologies on green innovation behavior for green innovation performance. Moreover, the mediating role of open innovation paradigm is studied between Industry 4.0 technologies and green innovation behavior. Previously, open innovation model is mainly used and applied in multinational firms whereby they focused to improve their innovations to stay competitive and financially stable, and profitable through innovations. However, this study is markedly contributing to bring open innovation paradigm for sustainability, environmental-friendly and green innovations, particularly for SMEs. Our study is also in line with one of the key Sustainable Development Goals set by the United Nations to promote sustainable and environmentally friendly innovations (UN-DESA, 2020). In the next section, relevant literature is synthesized, and hypotheses are developed. In the third section, the methodology is formulated, followed by Section 4 in which data analysis is performed and findings are articulated. Finally, discussions are made, and the study is concluded.

2. Literature review

2.1 Industry 4.0 technologies

In this progressive world, Industry 4.0, the fourth technology transition, is known as a huge cross-disciplinary term. Piccarozzi *et al.* (2018) highlighted that the concept of Industry 4.0 was initially developed in an engineering field, nevertheless it grew and expand in other fields as well which are such as economics and management. According to the technological scenario, the fundamental of Industry 4.0 is set up on rapid growth of IoT and CPSs, providing digital telecommunications measures and facilitating communication between physical and cyber components (Atzori *et al.*, 2010; Khaitan and McCalley, 2014). Industry 4.0 is defined as "the fourth industrial revolution applying the principles of cyber-physical systems, Internet and future-oriented technologies and smart systems with enhanced human-machine interaction paradigms" (Sanders *et al.*, 2016, p. 816).

Likewise, Pan *et al.* (2015) stated that "Industry 4.0 represents the ability of industrial components to communicate with each other" (p. 1537) Both definitions highlight the characteristics of interaction and communication between humans and machines, which involve the use of the IoT approaches and result in the production of large quantities of data. Russman *et al.* (2015) take both machines and humans into consideration and express Industry 4.0 as "a new digital industrial technology" (p. 3) that ensures the "connectivity and interaction among parts, machines, and humans" (p. 2), and it will transform the manufacturing "from single automated cells to fully integrated, automated facilities that communicate with one another" (p. 2). Industry 4.0 technologies allow firms to reduce the number of resources wasted and the emissions, generating an overall environmental benefit as well as a reduction of the marginal production cost. This scenario shows that Industry 4.0 does impact green innovation performance in a positive direction. The authors further elaborate on Industry 4.0's leading technologies which include big data, CPSs, IoT, as well as blockchain.

One of the leading technologies of Industry 4.0 is Big data. Big data is a popular Industry 4.0 technology that can manage large quantities of data such as transmission, collection, structured and unstructured data processing for decision-making as well as storage (Vidgen, 2014). Furthermore, it adopts a systematic approach to identifying and explicates knowledge as original thoughts (Mubarak *et al.*, 2019a, b). Consequently, through the introduction of big data analytics, the credibility and reliability of vendors, partners and other stakeholders may be assessed by evaluating their past performance records, company portfolio and partnerships. In this manner, it can strengthen the green innovation mechanism for selecting the best supplier, investor, cocreator or contributor. Manufacturing firms created their identity as a faithful organization that fulfills the needs of society, and the aspirations of society. Therefore, big data is a technology that provides remedies not only to heal the environment but also to upgrade the quality and standard of life in society (Mehmood and Mubarik, 2020; Alcácer and Cruz-Machado, 2019).

Moreover, the CPS is an innovative technology that can engage with humans through integrated computational and physical devices by using interactive modalities. Practicing CPS, businesses may interact and collaborate without physical control or assessment with potential suppliers or collaborators to conduct green innovation processes (Lee *et al.*, 2019; Nawanir, 2016). CPS may also be a powerful strategy to streamline the network of green innovation to cocreate, collaborate and partner where information sharing, communication and computation are considered as core functions.

Furthermore, IoT is gradually being embraced by a variety of industries. It is seen as an evolving trend, an existing strategy, a tremendous innovation, alongside a popular expression in the academy and industry. Initially, IoT involves identifiable objects linked with the aid of radio frequency identification or RFID that can transform businesses. Nevertheless, experts have now defined IoT as a network of connected devices via the Internet or satellite. IoT is now used in a variety of sectors, such as transportation, smart home management, health and many self-propelled industries. Key technologies used by IoT include RFID, software and hardware applications, middleware and cloud computing. A firm can streamline its internal and external collaboration process by using IoT to store, exchange and disseminate its valuable information in a smart way without requiring human interaction. This could encourage a productive green innovation behavior while improving green innovation performance.

Other than that, a blockchain is an information-based technological tool that facilitates the process of data storage. This technology records information that allows different stakeholders to exchange and access similar information and data in a confidential manner (Koh *et al.*, 2020). Once the input of data is done in the blockchain, it cannot be modified or removed. Besides, it has high security and privacy and works as a database and network as it functions based on mathematically programmed defined rules (Chang *et al.*, 2020). This technology is an integration of digital databases as well as enterprise system. Blockchain can record every kind of transaction. These records are then used and shared within a large and decentralized network. Authorized stakeholders will be benefited because the records can be accessed efficiently (Feng *et al.*, 2020). Blockchain is also well known as an incorruptible digital ledger, not limited to financial or economic transactions, but virtually all, including tangible and intangible products and processes (Viriyasitavat and Hoonsopon, 2019; Mubarik *et al.*, 2021c). Blockchain, when combined with IoT, robotics and CPSs, could become a highly sophisticated tool for enhancing the quality of green innovation performance in a manufacturing firm that is vital to the future of technological advancement (Accenture, 2015; Mubarik *et al.*, 2020). In doing so, companies can cultivate their sharing networks through blockchain, where they can conduct sharing of real-time research and developments, expert knowledge safely and uninterruptedly.

2.2 Green innovation performance

Nowadays, green and eco-friendly innovations are increasingly catching the attention of researchers and policymakers. Green innovation is considered as hardware or software developments related to green products or processes, including innovations in energy-saving, pollution-prevention, waste recycling, green product design or corporate environmental management technologies (Chen *et al.*, 2006; Tang *et al.*, 2020). Green innovation is used to improve the efficiency of environmental management to fulfill the environmental security criteria (Lai *et al.*, 2003). Green innovation is classified into GPI and green product innovation. GPI refers to green process technology such as cleaning processes, emission control, pollution prevention, environmental performance and recirculation, with new or modified measures adding to the environmental insights for the development of products or services. Green product innovation refers to the essence or purpose of the products or services of an organization that is new or substantially improved in terms of the environment (Chen *et al.*, 2006). In this research, we will concentrate on the performance of GPI as well as green product innovation. Green innovation has recently earned a lot of attention in the manufacturing firm. Therefore, it is necessary to make great efforts to minimize the amount of waste and pollution produced in the production process and maximizes the use of resources by implementing and applying Industry 4.0 technologies.

In the past, several businesses questioned the feasibility of green innovation and overlooked it as an added burden due to costs anticipated for green innovation and the issue of whether information and technology can be achieved through green innovation and correlated to actual business performance. If all businesses that are expected to carry out green innovation are burdened with the cost-benefit effects of achieving green innovation, they should "work together to ensure that sustainable development is possible" through Industry 4.0. Kim *et al.*, 2016 proposed that manufacturing firms that have chosen to aggressively adopt green innovation environmental management should explore how to incorporate within the business or use intercompany environmental management and technology to achieve the aim of environmental regulation. Ma *et al.* (2018) also argued that, relative to other forms of innovation, green innovation is more likely to collaborate because it is easier to be together than to be alone. Cooperation on environmental issues offers businesses the ability to minimize costs and encourages companies and companies to step together in a better direction. Green innovation must, above all, be sustainable in that it contributes internationally to environmental problems and thus has greater external consequences than other forms of innovation. Since green innovation is a necessity, every firm should be actively involved to improvise the performance through initiatives such as Industry 4.0.

2.3 Green innovation behavior

Global environmental issues such as natural resource depletion, climate change and loss of biodiversity lead to the incremental interest of policymakers to promote green behavior (Li *et al.*, 2019). Green innovation involves intentional and organized action. Researchers with green innovative motives only and through the aggregation of green innovative and subjective patterns will participate in green innovative activities. As a result, the greater the researchers' enthusiasm for green innovation, the more likely it is to turn their goal into action. Simultaneously, previous research has shown that behavioral development can promote actions in various fields.

Various studies have recently explored the effect of the manufacturing industry's activities on environmental problems (Stern, 2000; Koger and Winter, 2011; Ogiemwonyi *et al.*, 2019). Human relation with the environment differs by definition. Green behavior has many concepts that are used interchangeably. Some of the names are "environmentally

supportive behavior", "pro-environmental or low-carbon behavior", "green behavior", "ecological conscious consumer behavior", "pro-environmental consumer behavior", "sustainable consumer behavior", "environmentally conscious consumer behavior", "environmentally friendly consumer behavior", "green consumer behavior" (Straughan and Roberts, 1999; Stern, 2000; Thøgersen and Ölander, 2003; Gan *et al.*, 2008; Jansson *et al.*, 2010; Kaufmann *et al.*, 2012; Fu *et al.*, 2017; Dabija *et al.*, 2018). Individuals that understand environmental realities and make attempts to improve their actions at the point of buying are considered green customers of green behavior (Ogiemwonyi *et al.*, 2019). In particular, green behaviors vary and have been categorized. An industry that purchases eco-products and reuses personal household products exhibits the adoption of private green behavior. Whereas when industry engages in sustainable activism and promotes environmental policy demonstrates a public green behavior (Huddart-Kennedy *et al.*, 2009). The awareness and action were taken by the employees in manufacturing industries by considering the environmental issues illustrate green behavior, which directly leads toward the solution of the environmental problems and concerns.

2.4 Open innovation

The open innovation approach emerges as a suitable approach to promote innovation especially for the firms equipped with Industry 4.0 technologies such as blockchain, IoT, CPSs and a few others (Mubarak and Petraite, 2020). Open innovation is termed as "systematically relying on a firm's capabilities, of internally and externally carrying out the major technology management tasks, along the innovation process" (Lichtenthaler, 2011, p. 77). According to Chesbrough (2003, p. 1), "open innovation as a model enables businesses to build a structured innovation ecosystem that uses networks of external partners and focuses on developing core internal competencies." It is an interfirm network that helps firms to innovate frugally without amassing in-house knowledge rather than utilizing outside knowledge to innovate or improve the existing products, services or processes (Asakawa *et al.*, 2010; Lichtenthaler and Lichtenthaler, 2009). Open innovation replaces the traditional rivalry among firms by introducing the coopetition, cooperation and collaboration notion (Chesbrough, 2006).

The dominance of Industry 4.0 advanced technologies has even more, increased the importance of this concept. Open innovation caters inside-out, outside-in and coupled innovation processes. Whereby, inside-out involves the outflow of internal knowledge of the firm to partners. Internal knowledge and information, which can also be called surplus research to generate external value. The inside surplus knowledge could have been discarded or wasted without applying the open innovation which nowadays firms could encash by sharing with external stakeholders (Savitskaya *et al.*, 2010). The outside-in process includes the inflow of external knowledge from partner firms to inside the firm. This form of knowledge is obtained through licensing in, spinning and collaboration with external partners to enrich the internal knowledge base (Salampasis *et al.*, 2014). Further, the coupled process is joint-working and alliance by using inside-out and outside-in knowledge in the form of, for example, cocreating and joint venture on a particular project (Chesbrough, 2020). Gassmann and Enkel defined it as "linking outside-in and inside-out by working in alliances with complementary companies during which give-and-take is crucial for success" (Gassmann and Enkel, 2004, p. 1). The notion of open innovation resides in the multiple mutual collaborations with external stakeholders to help improve the in-house knowledge base by utilizing outside knowledge, which plays an instrumental role in developing a mutual competence. This competency supports firms to enhance the streamlining of their innovation processes (Gassmann and Enkel, 2004; Petraite, 2020). In doing so, the innovation processes will become sustainable to reduce extra innovation-based investments and innovation behavior among the employees will be enhanced while doing collaboration and innovation-

based interaction with outside partners. If these interactions are focused to enhance the environment-friendly innovations which are posed to improve and promote green products and processes in the long run (Yang and Roh, 2019). These green products and processes are aimed to reduce the carbon footprint of firms to save the planet, hence, firms carry out their innovations accordingly. In this connection, open innovation among the firms or between the diverse stakeholders and companies will enhance the efficiency and sustainability of green innovations (Yang and Roh, 2019).

3. Hypothesis development

3.1 Industry 4.0 technologies and green innovation performance

Industry 4.0 strategies can enhance energy, facilities and the use of human resources (Lasi *et al.*, 2014). Industry 4.0 is a future-oriented framework, promoting the growth of autonomous production processes using big data, IoT, CPS and blockchain (Mubarak *et al.*, 2019a, b). A new sensor based on technologies is allowing manufacturing firms to track the use of machines, energy requirements and staffing preparation constantly. Data can be analyzed from multiple IoTs instruments to boost the sustainability of manufacturing activities by extensively evaluating the different Industry 4.0 innovations (Song and Wang, 2016). In order to maintain green innovation performance in manufacturing operations, products must be produced in a way that protects the environment, is socially viable, and is economically sound. Ethical and sustainable production processes-based production systems are a highly productive way to conserve energy and natural resources. According to Shivajee *et al.* (2019), the usage of quality management and digital tools enhances the manufacturing processes. Industry 4.0 has socio-technical technologies in which economic, social and organizational opportunities converge (Beier *et al.*, 2020). The performance of green innovation can be enhanced by the adoption of Industry 4.0 technologies. The manufacturing supply chain should be aimed at sustainability for saving consumption of energy, reducing and its environmental effects. Industry 4.0 could resolve the problems of ethical and sustainable supply chains (Yadav *et al.*, 2020; Mubarik *et al.*, 2021a, b). Green innovations lead to ethical and sustainable operations when environmental measures are employed across the product's life cycle (Gurtu and Johny, 2019; Kerin and Pham, 2019). Piyathanavong *et al.* (2019) also confirmed that awareness and investment in Industry 4.0 technologies are necessary to improve the green innovation performance. Therefore, this study formulates following hypothesis.

H1. Industry 4.0 technologies put a positive impact on green innovation performance.

3.2 Green innovation behavior, Industry 4.0 technologies and green innovation performance

A new approach to sustainability has been implemented by the fundamentals of the closed supply chain (circular economy). It has become important to promote reusing and recycling methods. Awareness of sustainability is significant to develop green innovation behavior among societies. Human behavior affects the decision-making of every organization (Lieder *et al.*, 2017). The development of green innovation behavior will add on more environmental and digitization benefits. The digital practice will dramatically lead to sustainable growth by reducing carbon footprints, the use of clean energies and technology solutions for people as well as society (Kumar, 2020). Industry 4.0's growth leads more transparently to efficient utilization of energy (Dutta *et al.*, 2020). Industry 4.0 processes, productivity in the manufacture of goods and creativity that affect social and environmentally sustainable growth can be strengthened by adopting green innovation behavior (Ghobakhloo, 2020). Thakur and Mangla (2019) claimed that emerging economies professionals in the manufacturing organizations for home appliances should concentrate on human,

organizational and technical aspects of sustainable supply chains. Government regulations, environmental consciousness and information technology are the main components in the implementation of circular businesses (Bhatia *et al.*, 2020). Moreover, Chauhan *et al.* (2019) discovered that manufacturing firms can also improve green innovation performance and Industry 4.0 if there is a strong impact of green innovation behavior. Thus, this research assumes the following:

H2. Green innovation behavior mediates between Industry 4.0 technologies and green innovation performance.

3.3 Open innovation mediates Industry 4.0 and green innovation behavior

In the upgradation of green innovation, open innovation plays an instrumental role to promote sustainability and efficiency (Yang and Roh, 2019). Undoubtedly, green innovations contribute mainly toward environmental sustainability, however, to perform and execute them requires a major restructuring ad jumping over existing technologies and processes which is a momentous challenge for firms. They have to do extensive research to improve their knowledgebase to reshape the interaction, priorities and behavior of all stakeholders, according to the sustainable and green innovation measures. However, firms cannot achieve this by acting in their silhouettes in isolation, instead they are required to pool-up their efforts by collaborating, cooperating and cocreating with each other – which cannot be done without adopting open innovation approach (Chesbrough, 2020).

Previously, research focused on knowledge diffusion mainly through external R&D in the form of sourcing, however, open innovation quested to include the inflow as well outflow of knowledge by replacing the notion of completely sourcing the knowledge domain and introduced the collaborative efforts, joint-working and cocreation (Chesbrough, 2006). Across the world, firms are collaborating with the trusted partners to enrich their knowledge and research-base for improving their (green) products and process.[28] Open innovation premise can improve the green behavior for green innovation with the help of Industry 4.0 technologies (Yang and Roh, 2019), which improve the collaboration, coopetition and cooperation among various partners (Mubarak and Petraite, 2020). Industry 4.0 technologies support open innovation practices through effective communication, knowledge accumulation, effective research and analytics techniques in CPSs. As a result, open innovation tends to contribute to the long-term goal including the fulfillment of environment-friendly and green innovation-related objectives (Tiwari *et al.*, 2018; Yang and Roh, 2019). Against this backdrop, we formulate the hypothesis as:

H3. Open innovation mediates the relationship between Industry 4.0 technologies and green innovation behavior for improving green innovation performance.

3.4 Conceptual framework

The conceptual framework of this study indicates that Industry 4.0 technologies influence green innovation behavior in firms which further leads to improving green innovation performance through green product and process innovation. Moreover, those technologies affect open innovation which further enhances green innovation behavior which then influences green innovation performance, as shown in Figure 1.

4. Research methodology

This study has applied a deductive approach of research in which the quantitative method is applied. In that, primary data are collected through structured questionnaires from SMEs from the manufacturing sector of Malaysia. The manufacturing sector contributes to more than 36% of the gross domestic product in Malaysia (Statista, 2020). For data collection, firms

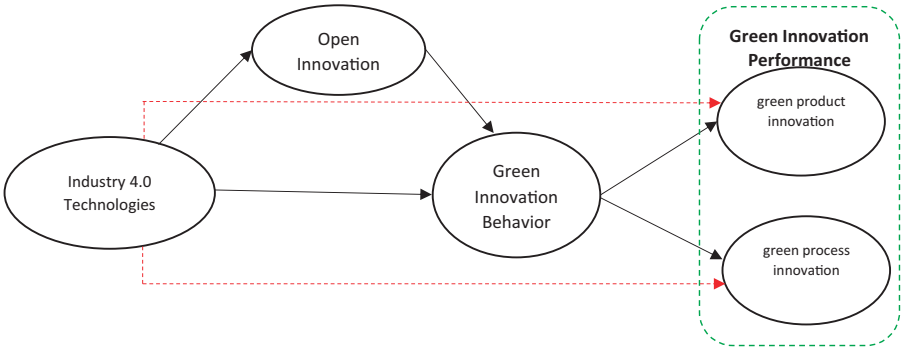

Figure 1.
Conceptual framework of the study

are chosen based on convenient sampling (Cresswell and Cresswell, 2017). A questionnaire was developed from previous studies with the constructs of Industry 4.0 technologies, open innovation, green innovation behavior and green innovation performance. The source and items of constructs are shown in Table 1.

The data collected was analyzed by applying the partial least square structural equation modeling (PLS-SEM) technique where the hypotheses of this research are tested. PLS-SEM is considered a highly robust modeling approach, which is applied in two steps. Firstly, it adopts a threefold approach to ensure the appropriateness of the measurement models for qualifying. Then, it includes an assessment of reliability, validity (convergent and discriminant) and model fitness. Finally, the model is analyzed to test the hypothesized relationship.

5. Results and findings

We received 217 responses from manufacturing sector firms of Malaysia mainly including electrical and electronics, chemical, rubber and plastic firms, food and beverages firms. The demographic details of respondents are highlighted in Table 2. Most of the firms, among respondents, are aged up to five years (53%), the remaining 33% are aged from 6 to 10 years, 10% have up to 15 years age, and only 4% are more than 16 years old. Moreover, 39% of respondents' firms include the electrical and electronics industry and the remaining are from other manufacturing industries.

For the purpose of analysis first of all reliability, consistency and validity tests are performed. The results show that the construct has internal validity and reliability whereby its value of Cronbach's alpha and composite reliability (CR) are more than 0.70, and its average variance extracted (AVE) values are more than 0.50 which indicates the appropriateness of our construct (Hair *et al.*, 2014). Factor loadings in Table 2 are more than 0.60, loadings less than this level were removed. Interestingly, the loading less than 0.60 was mostly less than 0.40 which were deleted (see Table 3).

Construct	Items	Sources
Industry 4.0 technologies	12	Kim *et al.* (2016), and Imran (2018)
Open innovation	10	Mina *et al.* (2014)
Green innovation performance	8	Chen *et al.* (2006)
Green innovation behavior	4	Li *et al.* (2019)

Table 1.
Questionnaire items and sources

In order to check the discriminant validity, we applied Fornell–Larcker criteria. The results show no multicollinearity issues, and the constructs have discriminant validity, as shown in Table 4.

After applying SEM multiple regression, we found the significant impact of Industry 4.0 technologies on green innovation behavior at p-value = 0.001 whereby the first hypothesis is supported. Moreover, the significance level at p = 0.248 for the second hypothesis indicates us to reject it. Then, the mediating role of open innovation between Industry 4.0 technologies and green innovation behavior for green innovation performance at p-value = 0.000 shows the significance and acceptance of Hypothesis 3. Likewise, Hypothesis 4 is also supported at

Table 2. Respondents demography (n = 217)

Firm age in years	Number of firms	% of firms
1–5	114	53
6–10	72	33
11–15	22	10
More than 16	9	4
Industries of firms		
Chemical	31	14
Rubber and plastic products	52	24
Food and beverages	49	23
Electrical and electronic products	85	39

Table 3. Reliability, consistency and validity

Construct	Items	Loadings	CB's alpha	CR	AVE
Industry 4.0 technologies	I4.01	0.68	0.72	0.81	0.56
	I4.02	0.72			
	I4.04	0.74			
	I4.06	0.70			
	I4.07	0.79			
	I4.08	0.81			
	I4.010	0.77			
	I4.011	0.84			
	I4.012	0.83			
Open innovation	OI01	0.75	0.81	0.87	0.51
	OI03	0.81			
	OI04	0.74			
	OI05	0.72			
	OI06	0.79			
	OI09	0.73			
	OI10	0.65			
Green innovation behavior (IB)	IB01	0.77	0.74	0.83	0.58
	IB02	0.88			
	IB03	0.75			
	IB04	0.67			
Green innovation performance (IP)	IP01	0.78	0.82	0.89	0.53
	IP02	0.73			
	IP03	0.80			
	IP05	0.81			
	IP06	0.75			
	IP07	0.74			
	IP08	0.79			

Note(s): Loading less than 0.60 were deleted

p-value = 0.004 at 95% level, where green innovation behavior mediated the relationship of Industry 4.0 technologies and green innovation performance (see Table 5).

6. Discussion and implications

The role of Industry 4.0 technologies is imperative to fulfill the sustainability motives of businesses through innovations. Focusing environmental perspective of sustainability, many researchers have described the positive role of Industry 4.0 technologies in improving open innovation which leads to enhance the green innovation behavior that further expands green innovation performance. In line with previous researchers including Mubarak and Petraite (2020) and Tang *et al.* (2020), the current study found the positive role of Industry 4.0 technologies on open innovation through enhancing cooperation, collaboration and coopetition. Thereby, it further promotes innovation behavior and especially green behavior in order to achieve green innovation performance (Chen *et al.*, 2006; Feng *et al.*, 2020). Likewise, green innovation behavior is inevitable to fulfill green innovation performance which contributes toward achieving the vision and goal of sustainability (Lai *et al.*, 2003; Li *et al.*, 2019). Hence, our study also confirms the positive impact of green innovation behavior on green innovation performance concerning green product innovation and GPI. Many researchers have suggested that technological orientation should also be involved in this connection which can complement the association of Industry 4.0, open innovation and green innovation performance (Mehmood and Mubarik, 2020). Moreover, it is also suggested to club technological absorptive capacity in such connection of technological orientation, Industry 4.0 and open innovation perspective in order to effectively yield green innovation performance robustly. Firms should incentivize the collaborative innovation-related projects that specifically focus green innovation and sustainable perspective. In doing so, not only they will contribute toward the ecological and environmentally friendly innovation for long-term benefit but in addition certain countries offer tax incentives and benefits for green innovation, in this way, firms could also get such benefits and reduce their costs. In this context, the open innovation-based collaborations could boost green innovation which is rarely accomplished in normal course of action without incentives.

Table 4. Fornell–Larcker criteria for discriminant validity

	VIF	I4.0	OI	IB	IP
Industry 4.0 technologies (I4.0)	1.92	*0.75*			
Open innovation (OI)	2.18	0.36	*0.76*		
Green innovation behavior (IB)	1.73	0.32	0.49	*0.74*	
Green innovation performance (IP)	2.19	0.35	0.37	0.41	*0.77*

Note(s): Diagonal values are square root of AVE

Table 5. Hypotheses testing

Hypothesis		p-value	Accept/ Reject
Hypothesis 1	Industry 4.0 technologies → Green innovation behavior	0.001	Accepted
Hypothesis 2	Industry 4.0 technologies → Green innovation performance	0.248	Rejected
Hypothesis 3	Industry 4.0 technologies → Open innovation → Green innovation behavior → Green innovation performance	0.000	Accepted
Hypothesis 4	Industry 4.0 technologies → Green innovation behavior → Green innovation performance	0.004	Accepted

7. Conclusion

Sustainability concerns with respect to environmental perspectives are in the limelight of policymakers, government authorities, businesses, researchers and academics nowadays. On one hand, innovations are facilitating businesses and customers alike, on the other hand, innovative technologies such as engines, etc. are continuously deteriorating the environment and ecosystem. Therefore, the need to promote green behavior and green innovation is imperative in order to move forward sustainably. With this mindset, the current study has examined the role of Industry 4.0 technologies to improve green innovation performance through promoting green innovation behavior with the help of open innovation approach to innovate. As a result, we confirmed the positive role of Industry 4.0 technologies in improving open innovation performance whom positive impact on green innovation behavior is revealed. Further, the positive impact of green innovation behavior on green innovation performance with respect to green product innovation and GPI is reported hereby. We recommend to policymakers and strategists to do the inclusion of open innovation approach, which is although an approach widely used in innovation management, in the connection of improving green innovation. Moreover, we also suggest that since our research catered to SMEs which are normally in more need of open innovation, owing to limited resources and low-risk bearing propensity. Our study investigated the given variables in SMEs of Malaysia in general irrespective of their role, impact and implementation in specific sectors. Thus, we suggest future researchers study sector-wise such as electrical and electronics sector, chemical sector, and others stand alone and then cross-comparison about their level of green innovation performance.

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