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Research Paper

Leveraging Big Data, Open Innovation and Digital Technology for Sustainable Environmental Performance: A Synergistic Approach

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Abstract

The purpose of this study was to investigate the relationship between big data, external knowledge, crowdsourcing, open innovation, digital technology and sustainable environmental performance in manufacturing sector in United States of America (USA). The study collected a sample of 373 responses and data was analyzed using JASP 0.19.0. The study found that the impact of big data is significant on external knowledge, open innovation and crowdsourcing. The study further found that external knowledge and crowdsourcing have a significant impact on open innovation and open innovation has a significant impact on digital technology and sustainable environmental performance. While the study also found that digital technology has a significant impact on sustainable environmental performance. The study is novel as previously there was gaps in literature, and recommendations of this study can foster a culture of sustainable environmental performance in manufacturing sector in USA.

Introduction

To fulfil the working on sustainable development goals, manufacturing organizations need to offer better environmental performances compliant with the sustainability requirements from regulatory agencies as well as end-users and pressure groups (Khaled et al., 2021). The toy manufacturing industry, in particular, has specific constraints: a strong need for raw materials and high energy consumption during production; creation of quasi-disposable waste material (toys) generating significant environmental risk at the end-of-life stage which is plastic-intensive. This presents the critical challenge facing toy makers today: What strategies can be developed to reduce their environmental impact and remain viable, going forward (Fatimah et al., 2020). This research is directing the solution of these issues towards the integration of green technologies based on open innovation, big data and external knowledge sources land. However, for these strategies to be put into practice, a greater appreciation of how each factor relates and influences environmental sustainability in the toy industry is needed (Kovačič Lukman et al., 2021).

Despite an emergent interest in sustainable practices within the manufacturing domain, a conspicuous lack of understanding appears with regard to how open innovation can be utilized to foster greater levels of environmental sustainability performance through toy making industry (He et al., 2024). It is notable that there has been an abundance of literature devoted to open innovation in general, frequently around high tech sectors or large corporations but hardly any about how, this could be achieved in the toys manufacturing industry (Hervás-Oliver, 2021). Likewise, opportunities for the big data and crowdsourcing in sustainable manufacturing practices are not well understood as relevant for integration with open innovation frameworks (Matricano et al., 2022). Although there is evidence supporting the crucial role of external knowledge sources and collaborative innovation strategies, scant research has yet to investigate ways in which these elements might help support sustainable outcomes for sectors like toy production that rely on massive environmental impact (Levesque et al., 2022), especially in United States of America (USA).

Moreover, extant research has mainly focused on the technological feasibility and costs of digital technology adoption, rather than concentrating on the organizational processes enabling its effective implementation (Saini et al., 2024). To the best of our knowledge, at least in toy manufacturers have not examined or reached an agreement on whether open innovation has a role to play opening up their model and subsequently closing that gap of technology adoption necessary for sustainable environmental gains in USA. Moreover, handling big data and leaning on external knowledge via crowdsourcing add another obstacle for these companies to contend with. Based on this complexity, it is really easy to assume that toy makers do not know how sustainable routes apply from one element within the system into another (Flores et al., 2022). Addressing this knowledge gap, the current study aims to examine the mediating role of open innovation in the relationship between big data and external knowledge with crowdsourcing while proposing sustainable environmental performance for a toy manufacturing plant.

The main aim of this research is to investigate the effect that big data, external knowledge, and crowdsourcing have on sustainable environmental performance in toy manufacturing

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firms with mediating role of open innovation. Furthermore, the study investigates the impact of digital technology on sustainable environmental performance, as the previous studies paid less attention to this relationship (Samuel et al., 2022; Wang et al., 2022). The focus on management-level employees, in this research is aimed at bringing out the business perspective of how decision-makers perceive and deploy such resources for sustainability goals in USA. We emphasize the contributions of this paper to advancing theoretical understanding of open innovation- digital technology dynamics and provide implications for action in practice by toy manufacturers who explore their environmental abatement ways. The results may provide better insights for firms when creating successful strategies merging innovation and sustainability in turn leading to an eco-friendlier manufacturing industry.

Review of Literature

What big data and external information signify for businesses today these days, big data goes hand in hand with machinery as well an external information (Kovacova et al., 2021). Data of this size takes advantage from being both structured and unstructured, falling under the broad term big data. On the other hand, external knowledge represents facts and insights that are manifested from outside sources of an organization such as market trends, which help in competitor analysis principles or scientific research enabling through collaborations, partnerships and open innovation (Zhang et al., 2020). Big data and external knowledge are complementary for organizational learning and decision making. Big data opens up a huge opportunity searching for hidden patterns, trends and insights which has not been possible previously via traditional sources. The right application of large external data combined with big data could offer organisations a more nuanced market and operational insight (Masiello et al., 2024). One common use-case is predicting industry trends using data mining on a high volume of competitor-related datasets, which paves the way for companies to change their strategies or develop new solutions that answer the call of changing needs.

In addition, big data analytics are enhanced through external knowledge contextual insights that make it clear and useful to understanding of all the facts discovered or confirmed by analytics from only within (Ehls et al., 2020). Big corporation, on the other hand, face a need to adapt quickly whenever real-world changes and integrate new tools, partners or customer metrics into big data-derived models as its typically time-consuming process. The synergy between these two schools of thought helps drive innovation quickly because the firms can better identify roadblocks and capitalize on opportunities by combining internal expertise with feedback from their ecosystem (Feng, 2024). Furthermore, a company can automate this process to an extent via machine learning algorithms which learn from analyzing the data and potentially improve itself as well by in turn feeding information back into it giving both big data and external knowledge loops informing on another (Zhu et al., 2016). Ultimately, this synergy leads to better decisions that add lasting advantage and foster sustainable growth.

H1: *There is a relationship between big data and external knowledge.*

Big data and open innovation complement each other, where big data is the crucial enabler of open innovation (Lepore et al., 2023). Big data represents a rich wrapper for open innovation, which is the practice of organizations going outside their own boundaries to reach external actors and yet obtain something valuable thereby. Big data is the term that describes it due to its volume, variety and velocity of access, but adding in veracity. Information helps in the idea generation, problem-solving and decision-making process which are the basic requirement to open innovation (Michalitsi-Psarrou et al., 2019). With the power of big data, enterprises are able to see trends and customer demand much more accurately which enable innovation driven by up-to-second insights. Big data analytics, when applied properly may help companies searching for external innovation that suits their strategy and potential partners with complementary assets & competences. Combining this with internal knowledge, companies can speed up the innovation cycle and improve the relevance of their offerings (Zhang et al., 2020).

In addition, big data intensifies the open innovation feedback circle as it allows businesses to test and optimize ideas perpetually with real-time analyses that in turn focus future innovations more on user benefit and market requirements (Flores et al., 2022). It even reduces the barriers for SMEs to participate in open innovation, as access to market insights which was typically restricted only at large corporations is made available (Ehls et al., 2020). However, utilizing big data for open innovation is not entirely straightforward, with the solution necessitating new ways to address concerns about privacy and control over information access; questions of how best to combine intellectual property outputs across multiple institutions in ecosystems that have been engineered more towards competition than collaboration; and a huge gap between simple machine-learning-based models being slowly integrated into decision-making versus solutions using sophisticated algorithms only considered further down the line. Consequently, organizations have to establish proper data governance frameworks in order for them to fully exploit the power of big data within open innovation strategies.

H2: *There is a relationship between big data and open innovation.*

Big data and crowdsourcing afford a symbiotic relationship where each reinforces the value of underpinning assets as well (Feng, 2024). Crowdsourcing is collecting information, services, or ideas from large group of people over internet channels which creates a lot of data that organizations can analyze to come up with sources of innovation and improvements in processes as well as decision making (Kovacova et al., 2021). The high-volume, varied nature of big data are fundamental components to effectively manage and analyze crowdsourced contributions. These platforms systematically gather vast amounts of data in the form of structured feedback, behavioral metrics and unstructured inputs, comments or ideas (Elsbach et al., 2013). Big data analytics can be used to analyze this unstructured data and get valuable insights, trends and public opinion on various topics. By the data analytics power of market research, crowdsourcing stands as an exploitable source that converts raw crowd input into actionable intelligence for new product design, issue solving and strategic planning (Buele et al., 2024). For instance, businesses might use big data analysis to sift through the thousands of ideas a company collects from public demos and rank them in terms of cohesion with potential solutions.

Big data further permits real-time monitoring of crowdsourcing initiatives; allowing firms to modify questions, goals and ways in which they interact with the crowd based on their responses and behavior (Michalitsi-Psarrou et al., 2019). In a software economy, crowdsourcing becomes particularly effective once data volume is very large: patterns and correlations hidden in massive amounts of unprocessed information can help organizations improve the accuracy with which they predict how users will act or what new requirements might emerge (Saini et al., 2024). However, challenges remain for the management of big data crowdsourcing due to expected issues with how trustworthy/valid and private these datasets are, we may experience many types of possible intrinsic biases in crowd-contributed contents in USA. More robust data management procedures need to be put in place, both for maintaining accuracy of the data and ensuring that considerations around ethics are addressed (Zhang et al., 2020). In this way, both big data as well as crowdsourcing naturally complement one another to provide an ecosystem of feedback: the quality of crowd-sourced information improve the analysis output produced by big-data analytics and therefore generate a strategic value over using it together.

H3: *There is a relationship between big data and crowdsourcing.*

At the very heart of open innovation and in particular what we describe as a core pillar informing its structure is this essential flow; this potential interplay between internal knowledge exploration directed by some defined research program tangible technology-concept seeking realization (Matricano et al., 2022). Open innovation, the structured processes for seeking out innovative ideas, technologies and expertise from outside an organization offers a way to bring different viewpoints together in creating new meaning (Hargadon et al., 2000). The idea is that it extends and broadens the possibility to innovate, allowing companies to push beyond their internal boundaries in term of expertise in resources or technology! In other words, a capacity for innovation (Johnson, 2001).

For that external knowledge, we have a number of different fields like relationships with universities, alliances for other firms and collaboration with customers or engagement through open platforms in what is often called crowdsourcing co-creation (Liu et al., 2018). This is valuable because the diversity of information that can be found cannot typically exist within an encapsulated organization. These third-party insights enable companies to track market trends, monitor evolving customer needs and adapt to technological advancements more immediately than would be possible via internal research alone (Michalitsi-Psarrou et al., 2019). The inclusion of learning from external sources within the realm of open innovation practices also leads to better diversification in terms of firms' basket for innovations, thus reducing their risk and increasing adaptability in a fast-moving market as well (Zhang et al., 2020). Teams could, as an example, bring agility and niche knowledge to mature firms through partnerships with start-ups or breakthrough scientific insights from collaborations with research institutions (Lepore et al., 2023). Open innovation through a dynamic learning perspective leads firms to utilize open resource in order for their capability of absorbing knowledge to be promoted and the dynamics or rapidity of adaptation within innovations is guaranteed.

Moreover, maintaining this balance when integrating external knowledge is another story that requires firms' coordination to navigate issues related to intellectual property management, reconcile different cultures and align the innovation objectives of outside-in with inside-out (Chen et al., 2016). Therefore, not only do external knowledge strengthen open innovation but it also requires new paradigms in terms of transferring and protecting (Bughin et al., 2008). It is through this symbiosis that ultimately enables firms to create, learn and commercialize innovation better than others, sustaining their competitive edge within an increasingly knowledge-based economy.

H4: *There is a relationship between external knowledge and open innovation.*

Crowdsourcing and open innovation are complementary to each other, whereby crowdsourcing acts as a fundamental tool used in the implementation of open innovation (Schlagwein et al., 2014). Crowdsourcing such as in open innovation, a practice that endorses the use of external knowledge and ideas to complement an organization's capability to innovate cannot be considered insignificant. Crowdsourcing involves organizations obtaining ideas, solving complex problems or solutions from a diverse and distributed group of external contributors, whose aspirations may be customers, experts in the field or broader public communities (Dolińska, 2018). This methodology boosts open innovation by facilitating insights and perspectives into a vast panorama far beyond the boundaries of traditional organizations. By incorporating crowdsourcing in open innovation, organizations have the capacity to benefit from "collective intelligence" acquiring perspective that is frequently both unique and user centric (Yun et al., 2019). By involving external contributors, organisations will bring into the room a deep knowledge that may expose new insights into gaining unique solutions or today's unmet needs when and where there may be future market opportunities that internal teams could easily oversight (Matricano et al., 2022). Secondly, it allows open innovation at a broader and more scalable level because firms can now gather contributions from diverse audiences around the world who will further initiate inclusive and diversified innovation process.

Crowdsourcing speeds up the ideation phase of open innovation as it enables you to work on multiple ideas concurrently and verify them with crowdsourced inputs (Seltzer et al., 2013). This quick stream of ideas leads to better choices and results in clearly identifying innovative areas. Crowdsourcing also contributes to creating user engagement which drives more results that are directly as per the demands and needs of end users, hence fitting into market trends (Cricelli et al., 2022). Although having its rewards as we discussed, crowdsourcing in open innovation can be tricky due to concerns about intellectual property rights, quality control, and possible crowd bias. Processes for filtering, evaluating and integrating these inputs are needed in coherent ways by organizations (Buecheler et al., 2010). Crowdsourcing amplifies open innovation by expanding access to knowledge and accelerating idea generation, yet also necessitates management best practices in order for organizations to get the most from crowdsourced ideas.

H5: *There is a relationship between crowdsourcing and open innovation.*

The dynamic of open innovation and digital technology likewise is cen-tripetal (Urbinati et al., 2020). it can be seen that the more a development, production or distribution process integrates with society meteorically sustainable technologies the greater transitive power for open innovation (Kennedy et al., 2017). Therefore, in short digital technology is all about technological innovations that help mankind to avoid pollution, improve resource efficiency which needs a good amount of multidisciplinary knowledge and great investments on research to comply with quickly arising environmental standards (Noorda et al., 2024). With its focus on leveraging external knowledge and collaborative arrangements, open innovation is especially well suited to the task as it enables firms to access insights from a variety of entities that include universities, research organizations, governances' bodies and industry partners (Kennedy et al., 2017).

In other words, open innovation enables cross-sector knowledge dissemination and collaboration, which is essential to overcoming the technical as well as financial hindrances that are typically associated with green tech development (Mubarak et al., 2021). Firms may have exclusive access to world-class scientific research, environmental practices or exciting new digital technology concepts by involving external stakeholders in open platforms and alliances or through crowdsourcing (Liu et al., 2018). The multiparty approach hastens technology development and spreads out risks, as several parties pool resources, skills and knowledge to foster green innovation. In addition, open innovation helps in quickly scaling and diffusing digital technology solutions (Wang et al., 2019). Examples include collaboration and knowledge-sharing with their global counterparts to address the cross-border dissemination of sustainable practices and green technologies. This is important for solving global environmental concerns as it helps in spreading of the green innovations to industries around the world.

Nonetheless, challenges have arisen in managing intellectual property rights, data security as well creating a symbiotic environmental objective across many different stakeholders (Eisenreich et al., 2021). Resilience of collaborative digital technology initiatives will require standardized frameworks and digital governance ecosystems. In the end, this dynamic interaction of open innovation and digital technology enhances an organization's ability to produce adjustments for a sustainable future (Lv et al., 2021). Today, more than ever before, this relationship is critical as sustainable development has become a strong competitive advantage and, in many cases, an existential requirement for future resilience to natural changes on multiple fronts whether at the local or global scale.

H6: *There is a relationship between open innovation and digital technology.*

This discourse, we link to open innovation, as one of the key issues that allow organizations an improvement in environmental sustainability practices (Chege et al., 2020). The objective of sustainable environmental performance is to reduce ecological footprints, reserve natural resources richness and restore balance equilibrium requiring also nonstructural prevention which specially knowledge backgrounds with range approaches, new technologies for holistic management action (Bughin et al., 2008). In short, open innovation helps firms to solve a range of macro environmental problems defined by firm-level practices for environment-sustainability through managing interaction with external experts and resource sharing on a strategic level (Ehls et al., 2020). In practice, companies can collaborate with universities but also R&D departments of NGOs directly or through open innovation for example to develop greener techniques together. This is a collaboration solution to ensure that businesses have access to state of the market knowledge and best practice in waste reduction, resource efficiency and emission management which are pillars for long term sustainable environmental performance (Eisenreich et al., 2021). Open innovation also aids in testing and adapting sustainability solutions across geographies, increasing the flexibility of firms to develop their sustainable practices when environmental standards or regulations change.

Open innovation also promotes faster dissemination of digital technology across industries as well for the general practice and culture shift towards environmentally sustainable practices (Lv et al., 2021; Mubarak & Petraite, 2020). Furthermore, in the realm of sustainability, businesses may introduce environmentally friendly technologies across open source environments and cross-industry partnerships at scale all for a cleaner tomorrow (Saini et al., 2024). Beyond just reducing costs, this shared-process approach promises to make the enzymatic process more sustainable demure as well, allowing for even greater potential impact across a wide variety of industries looking to increase their environmental friendliness.

H7: *There is a relationship between open innovation and sustainable environmental performance.*

Environmental sustainability and digital technology are intricately related as the latter is indispensable in making environmental performance sustainable (Seltzer et al., 2013). Digital technology incorporates technological solutions to protect the environment and provide sustainable environmental performance via materials, energy or subsystems offers that are valuable alternatives for conventional technologies (Zhang et al., 2020). Digital technology is the vehicle that allows organizations and industries to implement these objectives in a way, so as not to cost too much. Digital technology gives us the tools to positively impact environmental factors like carbon emissions, water usage and waste production (Wang et al., 2019). Organizations are driven to change their traditional resource intensive methods and adopt the environmentally responsible alternatives of renewable energy, pollution control or efficient use. For instance, the progress of solar power, wind energy and green chemistry are decreasing our dependence on fossil fuels at a time when greenhouse gas emissions must also decline in order to facilitate long term ecological balance (Lepore et al., 2023). Advances in minimizing waste and environmental damage from improved water purification, to recycling effluents or chemistries during textile processing up front and eco-friendly substrates.

In addition, digital technology helps firms to be in line with environmental principles and global sustainable criteria by improving their potentiality to achieve or report a long term sustainability of the firm concerning its environment plays (Chege et al., 2020). In addition to meeting compliance mandates, this regulatory alignment will become a new nexus of your market strength as increasing consumer dollars flow cheerfully towards environmentally minded firms (Bughin et al., 2008). Furthermore, getting digital technology for sustainable environmental performance achieved comes with its own set of hurdles. Typical hurdles are the development and deployment costs, technological scalability and being able to integrate into existing infrastructure (Kovačič Lukman et al., 2021). Finally, firms need to tackle the life cycle effects derived from green technologies that would bring about unexpected side environmental impacts and provide additional "net" energy savings in how they meet sustainability objectives.

H8: *There is a relationship between digital technology and sustainable environmental performance.*

The framework of study is shown in **Error! Reference source not found.**.

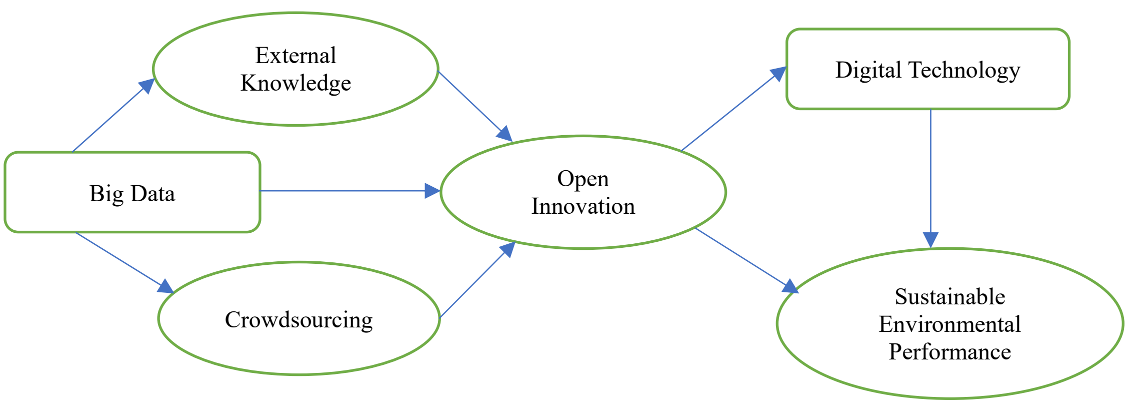

Figure 1: Framework of Study.

Methodology

Environmental sustainability is a critical goal of modern organizations. However, the stakeholders have a less productive attitude towards its improvement. This research has designed a questionnaire consisting of 7-point Likert scale instruments. These scale items are widely used in social sciences research to determine the perception and opinions of respondents and stakeholders. Therefore, the constructs used in this research are operationalized as per the context of the study. The construct big data is operationalized to determine the role of big data in advancing the external knowledge and open innovation of the employees. Furthermore, it is operationalized to investigate the impact of big data as a source of crowdsourcing. The scale items for big data are adapted from Wiesenberg et al. (2017). Secondly, this study has operationalized external knowledge as the external information possibly used for open innovation. The scale items for external knowledge are adapted from Ferraris et al. (2017). In accordance, the construct of crowdsourcing is operationalized to measure the impact of crowdsourcing on open innovation. The scale items for crowdsourcing are adapted from Xu et al. (2015).

Meanwhile, open innovation as a construct is operationalized to determine the role of open innovation in the advancement of digital technology and sustainable environmental performance. The scale items for open innovation are adapted from Zobel (2017). Likewise, the construction of digital technology is measured to determine the role of digital technology as a factor contributing to sustainable environmental performance. The scale items for digital technology are adapted from Li et al. (2023). Finally, the construct sustainable environmental performance is operationalized to determine the role of sustainable environmental performance in relationship with open innovation and green technologies. The scale items for sustainable environmental performance are adapted from Gholami et al. (2013). In this way, the questionnaire for this research is developed.

The respondents of this study are employees of manufacturing firms in the USA. Particularly, this study has targeted the employees of toys manufacturing firms' employees. The management level employees are selected as a research population. First, manufacturing firms in Wuhan were visited. The managers who are in charge of manufacturing units are targeted. The manufacturing managers of 400 organizations are considered as potential respondents. They were asked to provide data for this research. The top management consent was also taken for data collection. This research collected data on a single time, and cross-sectional method of data collection is considered. Furthermore, the data is collected with random sampling method because the population of the research is known. The survey-based approach is used to collect the data as it saves the time of researchers. For statistical analysis, JASP 0.17.3 is applied to investigate the descriptive statistics, unidimensional reliability, Pearson' correlations, and regression analysis.

Four hundred (400) questionnaires were distributed to the respondents physically in the USA. The respondents were asked to fill the questionnaire properly. However, 377 responses were collected back. The final sample size of this research is based on 373 responses as 04 responses were eliminated due to biased responses. These 373 respondents were manufacturing sector managers in their respective firms in the toy making sector. Furthermore, 153 respondents were female and remaining were male. In accordance, 201 respondents were Masters in their academia, the rest of them are Bachelors. In accordance, 112 respondents had more than ten years' experience, meanwhile, 97 respondents had experience between five to ten years. Remaining respondents have less than give year of experience.

Data Analysis

Descriptive Analysis

The normality of distribution of data is checked at the initial stage. The data is tested for missing values, and the findings determined that there are no missing values in the data. Furthermore, the findings of skewness and kurtosis are determined to check the normality of data. Likewise, a kurtosis and skewness between -2 and +2 indicates a distribution that is normal (Royston, 1992). When both skewness and kurtosis are close to zero, the pattern of responses is considered a normal distribution. The findings reported in **Error! Reference source not found.** confirmed that normality of data is achieved. Therefore, the data is reliable for further statistical analysis.

Table 1: Descriptive Statistics.

Constructs	Missing	Mean	Std. Deviation	Skewness	Std. Error of Skewness	Kurtosis	Std. Error of Kurtosis
BD	0	3.402	1.577	0.374	0.157	-1.129	0.314
EK	0	3.600	1.684	0.276	0.157	-1.140	0.314
CS	0	3.544	1.679	0.401	0.157	-1.044	0.314
OI	0	3.294	1.330	0.731	0.157	-0.310	0.314
DT	0	3.085	1.309	0.923	0.157	0.326	0.314
SE	0	3.112	1.250	0.913	0.157	-0.050	0.314

BD = Big Data, EK = Environmental Knowledge, CS = Crowdsourcing, OI = Open Innovation, DT = Digital Technology, and SE = Sustainable Environmental Performance.

Unidimensional Reliability

Table 2: Frequentist Scale Reliability Statistics.

Estimate	McDonald's ω
Point estimate	0.957
95% CI lower bound	0.949
95% CI upper bound	0.966

BD = Big Data, EK = Environmental Knowledge, CS = Crowdsourcing, OI = Open Innovation, DT = Digital Technology, and SE = Sustainable Environmental Performance.

The frequentist unidimensional reliability analysis allows the user to test the scale's ability to consistently measure a unidimensional construct. This analysis indicates the amount of error captured in the measurement. This study has considered Recommended way was used to measure the internal consistency between the items used for a single construct. Internal consistency is usually considered acceptable if the estimate is 0.70 or higher (Hayes et al., 2020). The data reported in **Error! Reference source not found.** confirmed that internal consistency between the research data is achieved.

Pearson's Correlations

Pearson's correlation coefficient is the test statistics that measures the statistical relationship, or association, between two continuous variables. The Pearson correlation measures the strength of the linear relationship between two variables. It has a value between -1 to 1, with a value of -1 meaning a total negative linear correlation, 0 being no correlation, and + 1 meaning a total positive correlation (Sedgwick, 2012). The data reported in Table 3 confirmed that there are significant correlations between the variables.

Table 3: Pearson's Correlations.

Variable		BD		EK		CS		OI		DT		SE
1. BD	Pearson's r	—										
	p-value	—										
2. EK	Pearson's r	0.935	***	—								
	p-value	< .001		—								
3. CS	Pearson's r	0.920	***	0.936	***	—						
	p-value	< .001		< .001		—						
4. OI	Pearson's r	0.843	***	0.829	***	0.812	***	—				
	p-value	< .001		< .001		< .001		—				
5. DT	Pearson's r	0.703	***	0.661	***	0.635	***	0.864	***	—		
	p-value	< .001		< .001		< .001		< .001		—		
6. SE	Pearson's r	0.631	***	0.605	***	0.590	***	0.835	***	0.905	***	—
	p-value	< .001		< .001		< .001		< .001		< .001		—

* p < .05, ** p < .01, *** p < .001

Regression Analysis

Regression analysis is a powerful statistical method that allows you to examine the relationship between two or more variables of interest. For regression analysis, $p < 0.05$ is considered is appropriate threshold (Draper et al., 1998). The regression results of H1 confirmed that a positive change in big data influence external knowledge positively. There is a positive relationship between big data and external knowledge ($p < 0.01$), and results are reported in Table 4.

Table 4: Regression Results (H1).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.600	0.109		33.048	< .001
	(Intercept)	0.206	0.093		2.231	0.027
H_1	BD	0.998	0.025	0.935	40.418	< .001

BD = Big Data

Furthermore, the regression results of H2 confirmed that a positive change in big data influence open innovation positively. There is a positive relationship between big data and open innovation ($p < 0.01$), and results are reported in Table 5.

Table 5: Regression Results (H2).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.294	0.086		38.281	< .001
	(Intercept)	0.875	0.110		7.929	< .001
H_2	BD	0.711	0.029	0.843	24.137	< .001

BD = Big Data

Accordingly, the regression results of H3 confirmed that a positive change in big data influence crowdsourcing positively. There is a positive relationship between big data and crowdsourcing ($p < 0.01$), and results are reported in Table 6.

Table 6: Regression Results (H3).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.544	0.109		32.634	< .001
	(Intercept)	0.212	0.101		2.092	0.038
H_3	BD	0.980	0.027	0.920	36.230	< .001

BD = Big Data

Table 7: Regression Results (H4 and H5).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.294	0.086		38.281	< .001
	(Intercept)	0.894	0.113		7.890	< .001
H_4	EK	0.442	0.080	0.560	5.511	< .001
H_5	CS	0.228	0.080	0.288	2.834	0.005

EK = Environmental Knowledge and CS = Crowdsourcing

Meanwhile, the regression results of H4 confirmed that a positive change in external knowledge influence open innovation positively. There is a positive relationship between external knowledge and open innovation ($p < 0.01$). The statistical data of H5 established that a positive change in crowdsourcing influences open innovation positively. Likewise, there is a positive relationship between crowdsourcing and open innovation ($p < 0.01$), and results are reported in Table 7.

Likewise, the regression results of H6 confirmed that a positive change in open innovation influence digital technology positively. There is a positive relationship between open innovation and digital technology ($p < 0.01$), and results are reported in Table 8.

Table 8: Regression Results (H6).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.085	0.085		36.426	< .001
	(Intercept)	0.284	0.114		2.481	0.014
H_6	OI	0.851	0.032	0.864	26.429	< .001

OI = Open Innovation

Finally, the regression results of H7 confirmed that a positive change in open innovation influence sustainable environmental performance positively. There is a positive relationship between open innovation and sustainable environmental performance ($p < 0.01$). The statistical data of H8 established that a positive change in digital technology influences sustainable environmental performance positively. Likewise, there is a positive relationship between digital technology and sustainable environmental performance ($p < 0.01$), and results are reported in Table 9.

Table 9: Regression Results (H7 and H8).

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	3.112	0.081		38.502	< .001
	(Intercept)	0.332	0.090		3.664	< .001
H_7	OI	0.196	0.050	0.209	3.923	< .001
H_8	DT	0.692	0.051	0.725	13.627	< .001

OI = Open Innovation and DT = Digital Technology

Discussion and Conclusion

The findings of this work also add to our understanding the inter-related influence of big data, external knowledge, crowdsourcing and open innovation in diffusion on digital technology application or implementation process that eventually contributes towards environmental sustainability among toy manufacturing firms in USA. All hypotheses were confirmed to enable an understanding of how these components contribute together towards the sustainability in industry. This discussion will focus on the details of each confirmed hypothesis, as well as their theoretical and practical implications.

Big data augments external knowledge (H1), the finding is consistent with prior literature that posits using big data may provide more capability to capture, transact and utilize large volumes of external information which will in turn lead a firm to trading knowledge. Big data in the toy industry grants them insights into market tendencies, consumer likings and technologies that are just emerging right now. All of these can be actively used to optimize marketing performances (Karpudewan, 2024). By doing so, companies are better equipped to take more informed decisions and adapt their practices in accordance with sustainable ambitions by integrating various forms of external knowledge (Buele et al., 2024). This finding should be especially valuable as big data is one of the most important sources for obtaining relevant knowledge necessary to survive competitive specific market change circumstances.

The positive influence of big data at further levels, confirmed by the H2 results open innovation praxis confirms that data indeed augments collaboration and adaptability in innovating processes. The tools provided by big data help companies to identify and capitalize on new market opportunities, fostering greater cross-functional and even intra-organizational collaboration (Flores et al., 2022). Through open innovation, companies can tear down data silos and share knowledge more broadly to gain a wider range of insights. In the area of toy production, this means that through big data analysis or proper use can be recognized which materials are sustainable to make toys out of and steps will improve manufacturing processes along with waste reduction all made possible by less competition (Hargadon et al., 2000). Therefore, this research supports the idea that big data serves as a core to open innovation which helps business to achieve sustainable solution using internal and external stakeholder network.

For H3, we note that the results are consistent with big data having a positive effect on crowdsourcing. This finding is consistent with earlier work claiming that big data can expand crowdsourcing by providing a platform for more large-scale, diverse input of ideas, solutions or feedback from the crowd (Xu et al., 2015). For toy manufacturers, crowdsourcing provides the ability to involve a large crowd in solving problems and generating ideas particularly when it comes to finding materials or products that are sustainable (Schlagwein et al., 2014). The synergy between big data and crowdsourcing reflects the contribution of collecting, processing, and working on information coming from external contributors (Wiesenberg et al., 2017). This study contributes to the literature by demonstrating how firms can use big data to make crowdsourcing a feasible, effective mechanism for promoting sustainable behaviours particularly in a sector where traditional practices typically restrict the opportunity for innovation.

The evidence supporting H4, that external knowledge is helpful when trying to be open in practice suggests benefits from using the firm s innovation ecosystem as a way of integrating new insights across sources. Companies like toy manufacturers typically operate in a very traditional way and their processes are resource heavy, so using external knowledge allows these companies to find new ways of thinking about sustainability and best practices for it (Li et al., 2023). This finding implies that firms adopting external knowledge realize higher potential to implement open innovation practices contributing to environment performance (Saini et al., 2024). In providing support for this relationship, the study highlights that external knowledge is an indispensable driver of innovation because it introduces both novel conceptual metaphors inspiring sustainable product designs and production processes as well as new strategic capabilities in business models (Gholami et al., 2013). These results could have significant implications in industries such as toy manufacturing that are responding to increasing consumer demand for eco-friendly products.

This research confirms (H5) that crowdsourcing does lead to higher levels of open innovation and thus that firms are effectively leveraging external contributors who do contribute with a positive effect on the likelihood of innovating within firms. Unlike traditional closed innovation, crowdsourcing stimulates a greater variety of input from many different perspective's customers, suppliers and the general public, providing an improved range of ideas to find sustainable solutions (Bughin et al., 2008). The bare fact is that, within the toy industry, where being imaginative and doing things new necessary conditions crow sourcing can deliver businesses in this business an increased community pool for sustainable materials used alternative options as well as eco-friendly packaging alternatives plus opportunities (Gholami et al., 2013). This brings out the nature of embedding crowdsourcing as not simply a means to store ideas but also build an operational spirit and support system that any sustainable innovation initiative demands (Li et al., 2023). Validating this link, the research adds to our understanding of crowdsourcing as one critical element in open innovation which is indispensable for firms striving sustainability implementation creators in the USA.

The results for H6 verify that open innovation has a significant positive effect on digital technology adoption. This supports previous findings aiming at opening up innovation to drive technological progress and sustainability. Open innovation promotes toy companies to research more alternative products or methods like using biodegradable plastics, recycle packaging and energy-saving technologies in production (Moshood et al., 2022). Adopting open innovation enables organizations to share resources, leverage risks and zero in on the knowledge they need for a successful digital technology deployment (Lv et al., 2021). This research contributes to strengthening the theoretical relationship between open innovation and digital technology by asserting that a collaborative has become entirely necessary in order for toy manufacturers to welcomely embed sustainable technologies back into their production process (Kennedy et al., 2017).

The conclusion that open innovation has a positive effect on sustainable environmental performance is also validated by H7. This suggests open innovation invaluable in supporting wider sustainability ambitions, enabling eco-innovations to enter the value chain at multiple points. Toy manufacturers, for example, can tap into open innovation to design products with a lighter environmental touch how plastic waste is reduced and eliminated in the process; things that keep up energy costs (Costantini et al., 2017). This speaks to the potential for open innovation as a critical vehicle in driving long-term environmental sustainability by encouraging firms to innovate while considering broader environment-related goals (Chege et al., 2020). This study then contributes to our understanding of how open innovation can help directly improve sustainability outputs for industries with an environmental footprint (Li et al., 2023).

Confirming H8, the study discussed that digital technology is, indeed, beneficial to sustainable environmental performance. Bringing the latest digital technology into use, toy firms make a contribution to addressing issues of nature conservation during resource extraction and production as well as waste processing (Lu et al., 2023). Companies can get a reinforced sustainable environmental performance by using eco-friendly technologies, saving the environment from pollution and reducing waste (Kanagaraj et al., 2015). The compliance analysis makes evident that the creation and deployment of green technologies as a way to achieve sustainability objectives is essential, especially in manufacturing sectors with traditional resource intensive processes (Wang et al., 2019).

Implications

The research findings can help in expanding the existing literature on sustainable environmental performance by exploring how big data, external knowledge and crowdsourcing directly influence an open innovation based process within toy manufacturing contexts in the USA. The study enriches the theoretical landscape on open innovation, turning it into a central orchestrator that enables effective resource orchestration for sustainable outcomes. This study is focused more on an under-investigated area in the literature, namely Open Innovation with its link to big data and crowdsourcing from a toy manufacturing perspective. Secondly, the research unpacks how digital technology can be considered particularly challenging or enabling us to adopt within manufacturing with limited access to high-tech resources typically emphasized in innovation literature. These findings add to a larger body of innovation literature by illustrating that collaborative and data-driven resources can allow traditional industries to reduce their greenhouse gas emissions. This finding further establishes a basis for exploring comparable models in other sectors, thereby progressing the boundary of open innovation to different industry landscapes.

This study provides multiple practical implications for toy manufacturing companies aiming at improving their environmental sustainability according to the results. This study seeks to enable manufacturers through their capability of utilizing open innovation for driving sustainability practices at industry 4.0 and emphasizes the mediating role as well that therefore, they are encouraged in a general way to build an organizational culture with key components such as; collaboration between stakeholders of knowledge sharing so then the manufacturer may effectively use big data, external knowledge or crowdsourcing on fostering sustainable business operations which cares more about environmental and societal aspirations when facing globalization. This framework can be used by the managers and decision-makers in the toy manufacturing industry to implement strategies that ensure to reduce their environmental impact as well as satisfy regular regulatory requirements. The research also highlights the need to develop informational infrastructures and collaborations with outside firms that are crucial for open innovation efforts. In the USA, this empowers the firms to work with new ranges of intelligence and inventive solutions needed for addressing intricate sustainability difficulties. Instead, this study indicates the potential of crowdsourcing to improve environmental performance and further suggests that uniting external stakeholders is key for mechanisms supporting sustainability initiatives within toy manufacturers. Such collaborative thinking can push innovation results as well as stakeholder allegiance that underpin the company's sustainability and corporate social responsibility approach. This research, in general, suggests an action plan for the firm that aims for environmental objectives but at same always voting to be competitive within the market.

Future Directions

Industrial environment, toy manufacturing still future research on open innovation in relationship between big data or crowdsourcing and sustainable environmental performance other application of this paper may analyze industrial environments beyond toys. More case studies comparing across industries, such as the cases presented in this article would give us a better picture of how sector-specific dynamics influence open innovation and its effectiveness towards sustainability. Furthermore, longitudinal studies may help to identify possible long-term impacts of open innovation on the environment and analyze how firms' sustainability practices change over time.

Research examining the extent to which open innovation and sustainability practices are facilitated or hampered through organizational culture should also be explored further. What other benefits may come from using big data and crowdsourcing to support environmental goals; How should leaders develop visions or innovation-oriented cultures to add value toward motivating employees in order that they align their tasks with the strategic pillar? A third research avenue pertains to the influence of digital transformation tools like artificial intelligence and machine learning technologies upon open innovation for sustainability. With the development of these technologies, new advancements in conjunction with big data and crowdsourcing for digital technology could be highly beneficial towards more effective sustainability strategies. Future research could investigate how the regulatory environment influences open innovation adoption for sustainability, particularly in industries more prone to being high on societal concern scales.

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CRediT Authorship Contribution Statement

Pirthipal Harvey Steven: conceptualization, data curation, formal analysis, investigation, methodology. project administration, resources, software, supervision, validation, visualization, writing original draft, writing review & editing.

Declaration of Competing Interest

The author confirms there are no relevant financial or non-financial conflicts of interest

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Ethical standards were upheld, and approval was not required since no biological or tissue samples were used.

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The author takes full responsibility for this work, which was completed without AI or LLM assistance.

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