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Original Article

Assessing Industry 4.0 readiness for environmental sustainability: an empirical study incorporating cultural preferences

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Abstract

This study aims to assess the readiness of Industry 4.0 technology for promoting environmental sustainability considering the cultural influences. Data were collected via survey questionnaires distributed among 73 companies in Malaysia. Structural equation modeling was employed to analyze the data. The findings indicate significant influences of cultural dimensions such as masculinity and collectivism on the adoption of Industry 4.0 practices. Leadership and human resource capabilities emerged as pivotal factors in facilitating the adoption of Industry 4.0 technologies for enhancing environmental sustainability. This research contributes by elucidating the critical role of cultural factors in shaping the implementation of Industry 4.0 technologies.

Keywords: industry 4.0; readiness; sustainable development goals (SDGs); sustainability; environmental protection; cultural preferences

1. Introduction

Industry 4.0, also known as the Fourth Industrial Revolution, is a technological advancement that combines advanced technologies such as internet of things (IoT), artificial intelligence (AI), big data, cyber-physical systems, cloud computing, robotics, and additive manufacturing to optimize industrial processes and establish smart factories [1]. This transformation enhances productivity, flexibility, and efficiency by enabling real-time monitoring, data-driven decision-making, and automation. The benefits are increased operational efficiency, reduced costs, enhanced customer experiences, improved product quality, and greater innovation [2]. In the context of Industry 4.0, environmental sustainability is an essential topic that has garnered attention. Due to pollution, waste disposal, and intensive use of raw materials, knowledge, and energy, the emergence of Industry 4.0 for manufacturing and the technologies that are associated with it, such as the Internet of Things (IoT) and cyber-physical systems, among others, has a significant impact on the environmental sustainability of today's businesses [3].

Human actions can deplete natural resources and jeopardize long-term survival if environmental sustainability strategies are not used [4]. However, there is another scenario in which knowing the future or making predictions necessitates a thorough comprehension of the past. Environmental sustainability is described as responsibly interacting with the environment to minimize the depletion or deterioration of natural resources and to allow for long-term environmental quality [5]. Environmental sustainability helps to guarantee that

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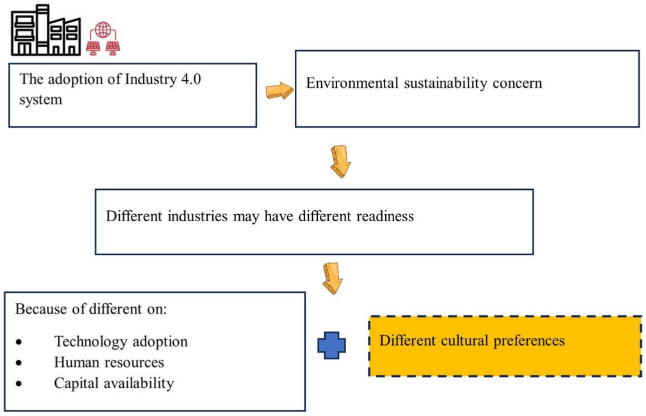

Figure 1. Different industries may have different readiness and cultural preferences.

today's population demands are addressed without affecting future generations' capacity to satisfy their own [6]. While the integration of Industrial 4.0 technologies holds significant promise for improving operational efficiency and productivity in manufacturing industries, there remains a notable research gap in comprehensively evaluating the readiness of these industries to leverage such advancements for environmental sustainability [7].

As depicted in Fig. 1, the existing studies predominantly focus on the technological aspects of Industry 4.0 adoption, overlooking the critical intersection with environmental concerns. However, the implementation of Industry 4.0 systems varies greatly between industries due to a variety of factors such as technological adoption, human resources, capital availability, and cultural diversity [8]. These discrepancies influence how equipped sectors are to implement modern digital technology and reap the rewards. While extensive study has been undertaken on the technical and economic elements of Industry 4.0 adoption, there is still a significant vacuum in understanding how cultural variations influence this process, particularly in terms of environmental sustainability [9]. Most studies have missed the importance of cultural elements in determining the readiness and effectiveness of Industry 4.0 efforts. This supervision is crucial since cultural attitudes and practices considerably impact technology integration and use [10]. To close this gap, this study aims to assess the influence of cultural variations on industry readiness to embrace Industry 4.0 technologies, emphasizing their impact on environmental sustainability. By exploring these cultural components, this study hopes to provide a more thorough knowledge of the problems and potential of implementing Industry 4.0 in a way that promotes sustainable environmental practices.

2. Cultural value

Culture is the collective mental programming that sets members of one group or category of people apart from others. Hofstede's cultural value dimensions offer a thorough framework for comprehending how cultural differences affect behavior and attitudes across nations [11]. These dimensions include long-term versus short-term orientation, high versus low power distance, masculinity versus femininity, collectivism versus individuality, and high versus low uncertainty avoidance. The degree to which people are integrated into organizations is measured by collectivism versus individualism, with collectivist cultures emphasizing social cohesion and individualistic cultures placing a higher value on personal autonomy and self-reliance [12]. The study of masculinity and femininity examines how the two sexes assign emotional roles to one another. Specifically, masculine cultures prioritize assertiveness, competition, and material success, whereas feminine cultures place a higher value on cooperation, quality of life, human health care, and caring for others [13]. The concept of power distance measures how much less powerful members of a society are willing to accept and even expect power to be distributed unequally. High power distance cultures are largely unquestioning of hierarchical order, while low power distance cultures strive for equal power distribution and democratic decision-making [14]. Low uncertainty avoidance cultures are more at ease with flexibility and taking risks, whereas high uncertainty avoidance cultures prefer organized surroundings and explicit regulations. Uncertainty avoidance reflects society's tolerance for ambiguity and uncertainty [15]. Finally, comparing long-term versus short-term orientation measures how much a culture values long-term gains over short-term gains. Long-term-oriented cultures value tenacity, thrift, and adaptability, while short-term-oriented cultures prioritize adhering to tradition, meeting social obligations, and producing results quickly. Comprehending these factors facilitates the analysis of how cultural environments impact economic policies, organizational practices, and the acceptance of technology in diverse societies [16].

3. Industrial 4.0 and environmental sustainability

Energy efficiency, leadership, human resources, air pollution reduction, technology, and water conservation are all part of the multidimensional strategy required to be Industry 4.0 ready for the environment. Energy efficiency is a pillar of sustainable industrial processes and environmental protection [17]. Real-time monitoring and dynamic energy usage optimization are made possible by using a powerful tool such as the finite element method [18–20], installing smart grids [21], sophisticated energy management systems, and Internet of Things-enabled sensors, which greatly lower carbon footprints. Equally important is leadership; visionary leaders are necessary to establish strategic sustainability objectives, obtain funding for cutting-edge technology, and promote an environment of ongoing innovation and environmental care inside companies. The foundation of this change is human resources. Hence, strong training and development initiatives that provide the staff with both technical know-how and a thorough awareness of sustainable practices are necessary [5]. Modern technology, which allows proactive management of environmental effects, such as predictive maintenance and real-time emissions monitoring, helps to reduce air pollution [22]. Technology is the core of Industry 4.0; breakthroughs in blockchain, big data analytics, and artificial intelligence offer the instruments required for increased operational effectiveness and less environmental effects. Industry 4.0 can be advanced, and environmental sustainability can be advanced by combining these components—energy efficiency, leadership, human resources, air pollution reduction, technology, and water conservation—into a higher state of readiness. Together with guaranteeing regulatory compliance, this integrated strategy positions sectors as leaders in sustainable

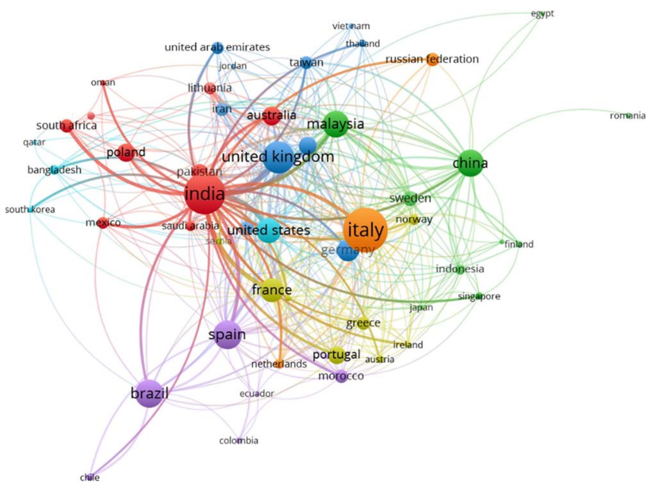

Figure 2. Data visualization on Industry 4.0 for environmental sustainability based on country.

Table 1. Research trend by country based on Scopus database

Country/territory	Number of articles
Italy	140
India	129
UK	85
Spain	72
Brazil	69
China	65
Malaysia	64
USA	58
France	54
Germany	48

development [23]. The study of Industry 4.0 for environmental sustainability has become more interesting worldwide [24]. This can be caused by the need to achieve sustainable development goals. This study noticed 10 countries that mostly research Industry 4.0 and environmental sustainability. The trend of the research is illustrated in Fig. 2.

Figure 2 and Table 1 describe that the top 10 worldwide research trends in Industry 4.0 and environmental sustainability have been expanding, with a noticeable emphasis on particular nations. With 140 published publications, Italy dominates the sector according to Scopus statistics covering 2005–24, underscoring its strong dedication to fusing cutting-edge industrial technologies with environmentally friendly methods. With 129 items, India follows closely, suggesting a strong emphasis on striking a balance between environmental issues and industrial expansion [25]. Furthermore, demonstrating strong research activity in this field are the UK with 85 papers, Spain with 72, and Brazil with 69. Contributing 65 and 64 articles, respectively, China and Malaysia demonstrate how important Industry 4.0 is becoming in Asia to solve sustainability issues. With 58 articles, the USA consistently desires to use technology to improve the environment. Contributing 54 and 48 pieces, respectively, France and Germany highlight their positions as significant European participants and support sustainable industrial developments [9]. The wide acceptance of Industry 4.0 as a crucial component in attaining environmental sustainability across various economic and geographical contexts is demonstrated by the worldwide dispersion of research efforts on Industry 4.0 and environmental sustainability as recorded by Scopus data [26].

4. Conceptual framework

Emphasizing automation, data interchange, and smart systems, the integration of Industry 4.0 technologies is completely changing manufacturing and production processes [27]. Still, cultural considerations greatly impact how prepared enterprises are to use this cutting-edge technology to support environmental sustainability [9]. Organizational culture affects attitudes toward innovation, environmental responsibility, and beliefs and actions. Strong emphasis on sustainability and environmental conservation makes societies more likely to give Industry 4.0 technologies that support green practices top priority and accept them. On the other hand, societies that do not give environmental concerns as much attention may adopt new technologies more slowly, maybe because they do not feel as urgent or necessary. Additionally important is the organizational culture of the companies; those that promote creativity, lifelong learning, and environmental responsibility can better put Industry 4.0 concepts into practice [28]. Developing plans to improve environmental sustainability across various industrial settings, therefore, requires an awareness of the cultural aspects that affect Industry 4.0 readiness.

Numerous scholars assert that culture is an entity or something ingrained in the everyday routine of the people living in an area. Put another way, culture is a universal phenomenon [29]. Every society has a culture that differs in all these ways because some cultures are passed down from predecessors. In contrast, others have developed over time to protect their way of life from the upheavals of a world becoming more and more technologically advanced [30].

The degree of individualism versus collectivism greatly affects Industry 4.0's environmental sustainability readiness. In collectivist cultures, collective environmental responsibility is usually more important than individual accomplishments since group aims and communal well-being are valued more highly. These cultures, seeing the benefits of Industry 4.0 technologies for the community at large, are more inclined to endorse and put them into use [31]. This cooperative strategy promotes industry and stakeholder cooperation, therefore promoting a concerted effort toward environmental objectives. Collectivist cultures also frequently have corporate and government policies that mirror societal values, which makes the regulatory environment more favorable for sustainable innovations [32]. Alternatively, unless it immediately benefits the person or organization, the emphasis on personal success and gains in individualistic cultures may lead to a less immediate prioritization of environmental sustainability. The main driver of environmental activities in an individualistic society may be commercial incentives to adopt green technologies [33].

Determining whether Industry 4.0 is prepared for environmental sustainability also heavily depends on the masculine versus feminine factor. Unless new technologies improve economic advantages, masculine cultures—defined by achievement, material success, and competition—may put technological developments and industrial expansion ahead of environmental concerns. In these cultures, sustainability projects could be taken up mostly if they are perceived to improve output and financial results [34]. On the other hand, feminine cultures—which emphasize social welfare, environmental protection, and quality of life—are more inclined to embrace Industry 4.0 technology that promotes sustainable practices [35]. These societies view the incorporation of such technology as a necessary element of environmental protection and society's well-being in addition to a way to promote industry. The focus placed on peaceful relationships and group well-being in feminine cultures can increase public acceptability and regulatory backing for sustainable technologies, therefore promoting a more comprehensive approach to industrial innovation [36].

Preparation for Industry 4.0 adoption with an environmental focus is influenced by the power distance dimension, which gauges how much less powerful people in a society accept and expect power to be divided unequally. Decision-making is centralized, and top management or government directions are usually complied with without question in high power distance cultures [37]. Adopting Industry 4.0 technology for this goal can happen quickly and successfully if executives prioritize environmental sustainability. Driven by authoritative instructions, this top-down approach can result in quick policy and technology deployment. There is more opportunity for grassroots projects and group decision-making processes that can promote broad support for sustainable technological integration, nevertheless, in low power distance cultures where power distribution is more egalitarian and participative. When many stakeholders participate in decision-making, an inclusive approach can produce more creative and context-specific solutions. By various means, high and low power distance cultures help Industry 4.0 prepare for environmental sustainability [38].

The way that sectors approach the adoption of Industry 4.0 technologies for environmental sustainability is influenced by uncertainty avoidance, which reflects the tolerance of ambiguity and uncertainty in society. Owing to perceived hazards, high uncertainty avoidance cultures that value clear rules and organized settings—may first be reluctant to adopt new, maybe disruptive, Industry 4.0 technology [23]. These cultures value stability and need a lot of data and legal frameworks before adopting new technology. However, after these technologies are shown to be useful and successful, these societies may then fully and methodically embrace them. Implementing sustainable technology thoroughly and in compliance with regulations can result from an organized approach. By contrast, low uncertainty avoidance cultures are more receptive to innovation and experimentation. As such, they may incorporate Industry 4.0 technology more quickly to improve environmental sustainability despite early uncertainties [39]. The receptivity of these cultures to novel experiences can promote the early adoption and incremental advancements of green technologies. As such, the degree of uncertainty avoidance affects the rate and mode of adoption of Industry 4.0 for sustainable practices [40].

Long-term versus short-term orientation affects how societies value future gains over immediate ones, influencing Industry 4.0 readiness for environmental sustainability. Viewing such investments as crucial for long-term success and survival, long-term-oriented cultures are more likely to invest in Industry 4.0 technologies that support environmental sustainability [5]. These values include perseverance, thrift, and adaptability to changing circumstances. Knowing the strategic value of sustainable practices for long-term success,

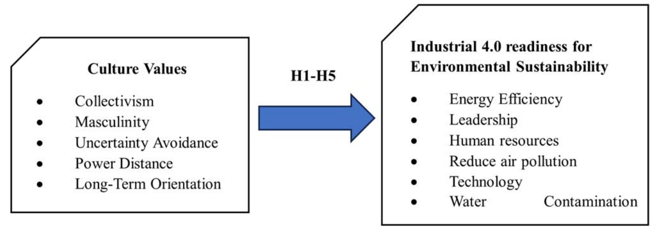

Figure 3. Research framework.

these cultures are prepared to pay now for future gains [41]. Proactive environmental laws and business plans that stress innovation and sustainability are frequently the outcomes of this future-oriented attitude. By contrast, cultures that are short-term focused prioritize quick wins and outcomes, which may result in a lower priority of sustainable practices unless there are obvious and immediate benefits [42]. When focused on the present, acute social or economic constraints may lead to reactive rather than proactive environmental initiatives. Since Industry 4.0 technologies stress sustainability and future benefits, long-term orientation positively correlates with the readiness to embrace them for environmental sustainability [16].

As explained above, five hypotheses need to be tested in this study based on the consideration of potential correlation. The hypotheses are depicted in Fig. 3.

1) There is a significant influence of collectivism on Industrial 4.0 Readiness for environmental sustainability.
2) There is a significant influence of masculinity on Industrial 4.0 Readiness for environmental sustainability.
3) There is a significant influence of power distance on Industrial 4.0 Readiness for environmental sustainability.
4) There is a significant influence of uncertainty avoidance on Industrial 4.0 Readiness for environmental sustainability.
5) There is a significant influence of long-term orientation on Industrial 4.0 Readiness for environmental sustainability.

4.1. Methodology

Seventy-three surveys in all were gathered from various Malaysian businesses. This work employed a self-administered methodology. To guarantee the accuracy of the data, a preliminary discrimination procedure was carried out to guarantee the respondent provided quality responses [43]. Thirteen responses in all were eliminated since they were incomplete. The minimal sample size was determined based on the Cohen general rule of thumb. The maximum number of arrowheads indicating the latent variable of the model created in this work served as the basis for determining the minimum sample size needed with a statistical power of 80%. For 11 pointing arrows, 59 samples with an R^2 of 0.5 were the minimal sample size needed. Since there were more respondents in the end than there was a minimal sample size, the sample was considered sufficient. There were 54 questions in all, divided into three parts. Gender, marital status, age, and position of the respondent were among the demographic details contained in the first part. CVSCALE, which was modified from the second part, was used to determine the cultural values of the consumers. Environment

Table 2. Demographic characteristics of the respondents

Demographic characteristic	Description	Frequency	Percentage
Gender	Male	36	54.4
	Female	30	45.5
Marital status	Single	22	33.3
	Married	44	66.7
Age	18–24	3	2.4
	25–34	22	33.3
	35–44	17	25.8
	45–54	12	18.2
	55–64	3	4.5
	65 Above	2	3.0
Position	Employee	29	43.9
	Manager	6	9.1
	Intern	11	16.7
	Supervisor	7	10.6
	QA/QC Manager	6	9.1
	Production Manager	0	0

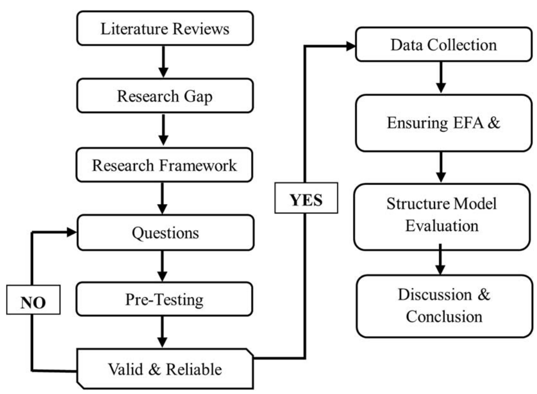

Figure 4. Research methodology.

sustainability and Industry 4.0 readiness were the topics of the final part. Every construction had five components in this area. The items in Section 3 were created concerning earlier research. Using the Likert scale from 0 to 10 (which indicates 'strongly disagree' to 'strongly agree' in Section 2 and 'strongly unimportant' to 'strongly important' in Sections 3 and 4), the respondents' mistakes were reduced, and the data's reliability was raised. Pretesting questionnaires were carried out to ensure the authenticity of the content. Table 2 has the specifics of the respondents' profiles, and the flow of methodology in this research can be seen in Fig. 4.

4.2. Goodness of measurement

Exploratory factor analysis (EFA) and Confirmatory factor analysis (CFA) were performed on the questionnaires to assess the data's reliability and the sampling's adequacy. The survey has reached a satisfactory threshold level, it is discovered. The overall Cronbach alpha coefficient is 0.923, which is higher than the necessary reliability threshold level of 0.7.

This study developed a hierarchical component model (HCM), which was analyzed using the partial least squares–structural equation modeling (PLS-SEM) approach. Second-order constructs, or higher order structures, are tested using the HCM model. The structural model's number of relationships was decreased in this analysis using the HCM, resulting in a more straightforward and concise PLS path. The

Table 3. Sample adequacy and reliability test

Measurement		Malaysia
Keiser-Meyer-Olkin (KMO) of sampling adequacy		0.908
Bartlett's test of sphericity	Approx. Chi square	10 994.20
	Df	1225
	Sig	0.000
Cronbach's alpha		0.923

KMO should be >0.5; Bartlett's should be significant, $P < .001$, Cronbach's alpha > 0.7

higher order component (HOC), which illustrates the abstract entity, and the lower order component (LOC), which records the abstract entity's subdimensions, comprise the two main parts of the HCM. Industry 4.0 readiness can be viewed as a multifaceted, abstract concept subject to various influences. The construct for Industry 4.0 readiness, represented as the HOC, is accompanied by a list of preferences that include reduced air pollution, water contamination, technology, leadership (management), innovation, and people (human resources) [44].

The principal component method-based factor analysis also reveals that every item has a factor loading and communality greater than the threshold levels of 0.5 and 0.3, respectively. The measurement model for CFA includes both formative and reflective measures. First, the reflective measures for the five cultural value dimensions were subjected to assessments of both discriminant and convergent validity. The evaluation of factor loadings, composite reliability (CR > 0.7), and average variance extracted (AVE > 0.5) are all part of the convergent validity assessment process. It is advised that the factor loadings fall between 0.4 and 0.7 or higher. On the other hand, removing the lowest items from the designated construct is better if doing so can raise the AVE and CR and remove the factor loading. Apart from items COL1 (0.554) and MAS4 (0.587), Table 3 shows that all the factor loadings for the five cultural value dimensions are sufficient. However, these numbers are still within the 0.4–0.7 critical threshold range. It is advisable to keep these two indicators since eliminating them has no discernible impact on raising AVE and CR. The final measurement model's factor loading, AVE, and CR for the five cultural dimensions are higher than the suggested threshold values, indicating sufficient convergent validity. App 6 was removed from the formative measurement because the outer loading was not significant and was <0.5.

The discriminant validity must be ascertained after the convergent validity has been confirmed. To confirm whether a construct is distinct from other measured constructs, state that a reflective measurement model must have established discriminant validity. The heterotrait–monotrait ratio (HTMT) was assessed to ascertain the discriminant validity. For the HTMT, 0.85 is the critical threshold. Discriminant validity can only be established if the HTMT is <0.85.

Given that the values are <0.85, Table 4 and Fig. 5 demonstrate that the HTMTs for each of the five cultural value dimensions meet the criteria for discriminant validity. This computation aimed to establish the foundation of statistical discriminant validity. It is discovered that the HTMT inference interval confidence value is less than the crucial 0.9 threshold. This demonstrates that the five cultural value dimensions have established discriminant validity. Furthermore, a collinearity assessment was conducted for the formative measurement

Table 4. Measurement model of the cultural value constructs

Cultural dimensions	Items	Loading	AVE	CR	Cronbach Alpha
Collectivism	COL1	0.554	0.583	0.843	0.842
	COL2	0.914			
	COL3	0.880			
	COL4	0.725			
Masculinity	MAS1	0.834	0.596	0.853	0.770
	MAS2	0.809			
	MAS3	0.828			
	MAS4	0.587			
Uncertainty avoidance	UAI1	0.752	0.623	0.892	0.854
	UAI2	0.802			
	UAI3	0.806			
	UAI4	0.856			
	UAI5	0.720			
Power distance	PDI3	0.435	0.581	0.710	0.406
	PDI5	0.981			
Long-term orientation	LTO1	0.876	0.842	0.955	0.940
	LTO2	0.930			
	LTO3	0.933			
	LTO4	0.933			

AVE represents the extracted average variance. AVE ought to be >0.5. Composite reliability is denoted by CR. A CR of 0.60–0.70 is appropriate for exploratory research

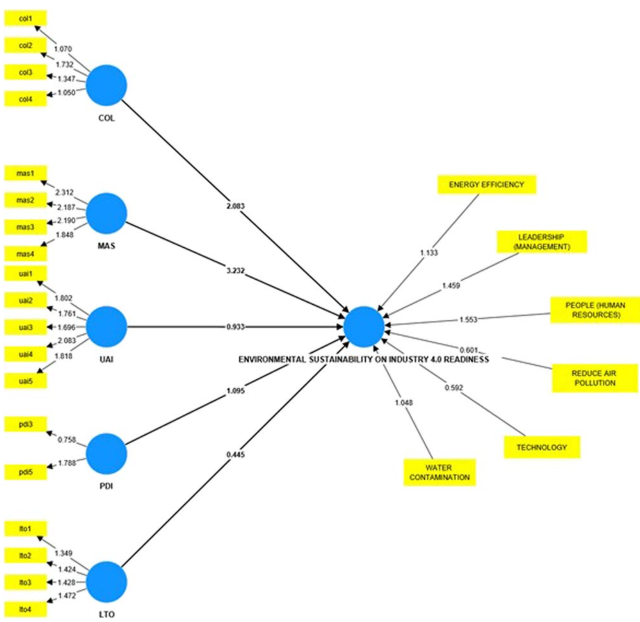

Figure 5. Structural modeling computation–Second Order Analysis.

model to ascertain the variance-inflated factor (VIF). The VIF is <5, suggesting that collinearity is not an issue.

Based on Table 5 and Table 6, masculinity (*t*-value = 3.232, *P* 0.01) and collectivism (*t*-value = 2.083, *P* 0.05) significantly influence Malaysian respondents' environmental sustainability and Industry 4.0 readiness, whereas long-term orientation, uncertainty avoidance, and power distance have no significant influence.

5. Discussion

This study aimed to identify Industry 4.0 readiness for environmental sustainability considering cultural influences [45]. A critical understanding of how cultural aspects and Industry 4.0 readiness for environmental sustainability in Malaysia interact is provided by the study's results. More precisely, the study shows that whereas long-term orientation, avoiding uncertainty, and power distance have little effect on environmental sustainability, masculinity and collectivism do [13]. Furthermore, a sophisticated knowledge of the relative relevance of different aspects is provided by examining outer weights for environmental sustainability indicators and Industry 4.0 readiness. This talk will go into these dimensions and the outer weight results, looking at their consequences and possible causes of the patterns that have been seen [46].

First of all, the strong impact of masculinity (path coefficient = −0.179, *t*-value = 3.232, $P < .01$) on the readiness of Industry 4.0 for environmental sustainability implies that the characteristics linked to this cultural dimension are crucial in forming attitudes and behaviors [47]. Culturally speaking, masculinity is essential to traditionally male characteristics like ambition, assertiveness, competitiveness, and the amassing of money and material achievement. Malaysia has modest levels of masculinity; hence, the emphasis on success and performance probably encourages businesses and people to use cutting-edge technology and environmentally friendly methods to gain an advantage over the competition. This is especially pertinent in Industry 4.0, where environmental sustainability and technical innovation can be considered as new platforms for proving competence and leadership [48]. Companies and people driven by these principles could see the incorporation of sustainable practices as a chance to demonstrate their innovative and forward-thinking attitude, improving their market position and reputation in addition to a legal need [49].

Second, under the Industry 4.0 context, collectivism (path coefficient = 0.144, *t*-value = 2.083, $P < .05$) likewise demonstrates a notable positive impact on environmental sustainability. Strong collectivist beliefs stressing community, familial relationships, and group harmony define Malaysian society [50]. This background of culture encourages a feeling of responsibility and teamwork toward shared objectives, such as environmental sustainability. Because the group's welfare is valued more highly than individual achievement in a

Table 5. HTMT for discriminant validity

	Power distance	Collectivism	Masculinity	Long-term orientation	Uncertainty avoidance
Power distance					
Collectivism	**0.146**				
Masculinity	0.291	**0.291**			
Long-term orientation	0.780	0.045	**0.299**		
Uncertainty avoidance	0.306	0.089	0.331	**0.487**	

Table 6. Result of structural model

Hyp.	Description	Path coefficient	Std. dev	*t*-value	Result
H1	Power distance - > Environmental Sustainability on Industry 4.0 Readiness	0.082	0.075	1.095	Not supported
H2	Collectivism - > Environmental Sustainability on Industry 4.0 Readiness	0.144	0.069	2.083**	Supported
H3	Masculinity - > Environmental Sustainability on Industry 4.0 Readiness	-0.179	0.055	3.232*	Supported
H4	Uncertainty avoidance - > Environmental Sustainability on Industry 4.0 Readiness	-0.054	0.058	0.933	Not supported
H5	Long-term orientation - > Environmental Sustainability on Industry 4.0 Readiness	0.030	0.067	0.445	Not supported

*$P < 0.01$, **$P < 0.05$, ***$P < 0.1$

Table 7. The Outer Weight results

Indicator	Industrial 4.0 readiness	Outer weight
IR3	Leadership (Management)	0.495
IR2	People (Human resources)	0.393
ES2	Water contamination	0.316
ES3	Energy efficiency	0.313
IR1	Technology	0.189
ES1	Reduce air pollution	-0.215

collectivist culture, people are more inclined to adopt environmentally friendly and, consequently, community-friendly actions. Organizations can be motivated by this collective perspective to put Industry 4.0 technologies—such as smart grids, waste reduction technologies, and energy-efficient manufacturing processes—into place. Together with improving environmental results, these programs also improve social cohesiveness and community relationships as companies and people collaborate to achieve a single goal [51].

As described in Table 7, the outer weight data analysis clarifies even more the important elements promoting environmental sustainability and Industry 4.0 readiness. As seen by the highest outer weight (0.495) of Leadership (Management) (IR3), visionary and strong leadership is essential to advancing Industry 4.0 projects and sustainable methods. This result indicates that the inspiring and mobilizing resources with a good leadership can encourage to match organizational concerns for continuously promoting sustainability goals [39]. Environmental performance can be improved by Industry 4.0 technology when leaders give sustainability top priority throughout the company [52].

The outer weight of 0.393 that follows People (Human Resources) (IR2) emphasizes how crucial human capital is to execute sustainability and Industry 4.0 projects effectively. Adoption and efficient usage of cutting-edge technologies depend on competent and driven staff. The performance and readiness of an organization can be significantly impacted by training and development initiatives that improve staff members' skills in sustainable practices and Industry 4.0 technologies [53]. Any technical change is built on human resources, and reaching sustainability objectives requires their involvement and knowledge.

Having outer weights of 0.316 and 0.313, respectively, Water Contamination (ES2) and Energy Efficiency (ES3) emphasize their vital responsibilities in environmental sustainability. Sustainable methods essentially include addressing water pollution and increasing energy efficiency [54]. Smart sensors and data analytics are two examples of Industry 4.0 technology that can be used to optimize energy use, low carbon-technology, and prevent water pollution, therefore promoting environmental sustainability and supporting human healthcare generally. These sectors are probably given top priority because of their obvious and immediate effects on the environment as well as running expenses [55]. With an outside weight of 0.189, technology (IR1) is not the most crucial component in Industry 4.0 readiness compared to leadership and human resources, albeit being significant. This implies that to reach its maximum potential, technology—while necessary—needs to be backed by capable personnel and good leadership [56]. To efficiently promote sustainability, technology integration must be strategic and in line with the goals of the organization and human resources. Interestingly, reducing Air Pollution (ES1) has a negative outside weight (−0.215), indicating a more intricate relationship or possible difficulties in this field. This would suggest that, as compared to other sustainability measures, attempts to reduce air pollution might encounter more significant obstacles or need more major adjustments in methods and technology [33]. It might also indicate a delay in implementing technologies meant to lower air pollution or give other environmental considerations precedence over air quality [57].

This paper clarifies the complex influence of cultural aspects on Malaysia's Industry 4.0 preparation for environmental sustainability [58]. While long-term orientation, avoiding uncertainty, and power distance have little effect, masculinity and collectivism have a significant impact that emphasizes the need for competitive drive and group responsibility. The outside weight analysis also highlights the vital contributions that, within the Industry 4.0 framework, leadership, human resources, and focused environmental initiatives make to sustainability [59]. These findings have important ramifications for company executives and legislators trying to promote environmental sustainability in culturally varied contexts through advanced technology adoption [60].

6. Conclusion

This study focused on the important elements affecting Industry 4.0 preparation for environmental sustainability by considering cultural influences. The results show that, whereas long-term orientation, avoiding uncertainty, and power distance have no effect on the adoption of sustainable practices within the Industry 4.0 framework, masculinity and collectivism do. Particularly, the adoption of cutting-edge technology and environmentally friendly practices to gain an advantage over competitors is driven by masculinity, which emphasizes success and competition. Conversely, collectivism promotes cooperation and shared accountability, therefore promoting environmental sustainability.

The outside weight study emphasizes the importance of human resources and leadership to Industry 4.0 readiness. Leadership (management) shows the most significant outer weight, emphasizing how vital visionary and capable leadership is to be advancing environmental projects. An innovative and continuously improving culture can be fostered, and strong leadership can match organizational aims with sustainability goals. Human resources come into a close second, stressing the need to have a trained and driven staff that can embrace and use cutting-edge technology for sustainable practices. Furthermore crucial because of their significant influence on both operational efficiency and environmental results are environmental sustainability metrics like water pollution and energy efficiency. Nonetheless, the unfavorable exterior weight connected to lowering air pollution raises the possibility that this field may encounter more severe difficulties that need appropriate solutions to get beyond obstacles and produce the intended results.

By including cultural aspects with Industry 4.0 readiness and environmental sustainability and offering a thorough grasp of how these elements interact in the Malaysian setting, this study adds to the body of knowledge. Through the emphasizing on the essential roles played by masculinity and collectivism, this study provides insightful information about how cultural values influence the adoption of technology and sustainable practices. Moreover, the results on the outer weights of different indicators offer a complex picture of the relative relevance of leadership, human resources, and particular environmental elements, which might direct further study and real-world applications.

The findings of this study are also expected to give more insight to decision-makers and corporate executives on the main areas to concentrate on to improve environmental sustainability and Industry 4.0 readiness. Organizations may more successfully negotiate the shift to Industry 4.0 by focusing on developing strong leadership and human resources and attending to important environmental aspects. The practical consequences of this study emphasize the requirement of focused approaches that take cultural aspects into account to guarantee that technology developments are successfully incorporated and used for long-term results. Through these initiatives, Malaysia may move closer to a more technologically advanced and sustainable future that is in line with international sustainability targets.

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Supplementary data

Supplementary data is available at *International Journal of Low Carbon Technologies* online.

Conflict of interest

The authors declare no conflict of interest.

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Data availability

The necessary data used in the manuscript are already present in the manuscript.

Statement of originality

The authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. The authors confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. The authors further confirm that the order of authors listed in the manuscript has been approved by all of us. The authors understand that the corresponding author is the sole contact for the Editorial process. The corresponding author is responsible for communicating with the other authors about progress, submissions of revisions, and final approval of proofs.

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

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The authors affirm that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Ethical statement

This study did not involve human participants or animals, and no ethical approval was required. All research procedures adhered to relevant ethical guidelines and best practices for nonhuman and nonanimal research.

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