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The Moderating Effect of Green Intellectual Capital and its Dimensions on the Relationship Between Cleaner Production Strategy and Sustainable Supply Chain Management Practices: A Neural Network Analysis

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التأثير المعدل لرأس المال الفكري الأخضر وأبعاده على العلاقة بين استراتيجية الإنتاج الأنظف وممارسات إدارة سلسلة التوريد المستدام: تحليل الشبكة العصبية

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Abstract

The study aims to explore the moderating effect of the green intellectual capital and its dimensions (human, structural and relational, or social intellectual capital) on the relationship between the cleaner production strategy and the sustainable supply chain management practices using neural network analysis. Data were collected from 275 workers employed by the major Iraqi sugar and oil production company. Findings support the moderating effect of the green intellectual capital and its dimensions, with relational, or social capital exhibiting the strongest effect on the relationship between the cleaner production strategy and the sustainable supply chain management practices. This suggests that developing social capital, alongside the other two dimensions of the green intellectual capital, may contribute to the effective implementation of the cleaner production strategies conductive to the sustainable supply chain management practices.

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المستخلص

تهدف الدراسة إلى استكشاف التأثير المعتدل لرأس المال الفكري الأخضر وأبعاده (رأس المال الفكري البشري والبنيوي والعلائقي أو الاجتماعي) على العلاقة بين استراتيجية الإنتاج النظيف وممارسات إدارة سلسلة التوريد المستدامة باستخدام تحليل الشبكات العصبية. تم جمع البيانات من 275 عاملاً يعملون في شركة الاتحاد لإنتاج السكر والزيت. تدعم النتائج التأثير المعتدل لرأس المال الفكري الأخضر وأبعاده، حيث أظهر رأس المال العلائقي أو الاجتماعي أقوى تأثير على العلاقة بين استراتيجية الإنتاج النظيف وممارسات إدارة سلسلة التوريد المستدامة. وهذا يشير إلى أن تطوير رأس المال الاجتماعي، إلى جانب البعدين الآخرين لرأس المال الفكري الأخضر، قد يساهم في التنفيذ الفعال لاستراتيجيات الإنتاج النظيف المؤدية إلى ممارسات إدارة سلسلة التوريد المستدامة.

1 Introduction

Hummels (2021) argued that the organizations find it challenging to align their operations to suit the environment-friendly production practices, in the recent years. This phenomenon is attributed to the concerns raised upon the environmental damage and the need for sustainable production practices. Various researchers emphasized the importance of cleaner production strategies that help in mitigating the carbon footprint of the organizations that manufacture products and offer services (Punj et al., 2023; Sullivan et al., 2018). On the other hand, green supply chain management practices have gained much attention in the recent years since it brings both societal and the environmental aspects into supply chain operations (Carter & Liane Easton, 2011; Seuring & Müller, 2008; Vachon & Klassen, 2008). Being a challenging road ahead for the organizations to cope up with, the role played by green intellectual capital is gaining prominence towards accomplishing success in terms of sustainability. Green intellectual capital encompasses the skills, expertise and the knowledge pool of the organizations towards eco-friendly production and logistics practices. It further corresponds to the intellectual assets that empower the organizations to develop, test and validate eco-friendly production strategies and mitigate its environmental impact. Intellectual capital is generally inclusive of various resources such as, green technology innovation, employee knowledge about the environmental management systems etc. (Chen, 2008). Green production strategies and sustainable supply chain management are intertwined with each other and their relationship eventually results in improved environmental efficiency in the organizational processes. On the other hand, the sustainable SCM practices ensures the organization's adherence to sustainability agenda over the entire line of supply. Irrespective of this, the successful implementation of the strategy heavily relies upon the availability of resources, support from the individuals and organizational culture. Thus, Chen (2008) mentioned that green intellectual capital encompasses human, structural and relational capital that may potentially impact the relationship between sustainable chain performance and cleaner production strategies.

In this background, the current study intends to determine the complex interplay between sustainable supply chain performance and cleaner production strategies with green intellectual capital and a few dimensions moderating the relationship. Through this study, the authors demonstrate the way how intellectual capital in the organization can be reaped for enhancing the efforts taken for sustainability and also improve the synergy between supply chain sustainability and cleaner production practices. The current study findings will be helpful for the organizations to gain knowledgeable insights on sustainable business practices and help them to have a smooth paradigm shift that helps them achieve organizational sustainability as well as environmental responsibility.

2 Theoretical framework and hypotheses

2.1 Cleaner production strategy

Giannetti et al (2021) mentioned that the cleaner production strategies were first conceived in the 1980s as a mandatory concept for the industries. The aim of this strategy is to mitigate the volume of industrial emissions as well as pollutants through preventive measures. In addition to this, the strategy also aimed at maximum utilization of waste and the by-products produced during the entire process (Sangwan & Mittal, 2015). Such concept was found to be non-linear from the conventional approach in which the pollutants are treated after its production. This not only incurred huge costs for the companies but also were inefficient. Cleaner production practices are generally applied across the production line such as manufacturing, marketing, services etc., with a sole purpose to achieve i.e., increased efficiency and mitigation of risks that harm the human health and the environment. This proactive process demands the cooperation at an individual, organizational and at the government level in addition to policy changes, behavioral and attitude change (Mugwindiri et al., 2013).

Giannetti et al (2021) cited the growing importance of cleaner production strategies in the recent decade, thanks to the development of environmental thinking. This approach strategizes the process to consume the least possible natural resources, preventing the organizations to leverage hazardous materials to the best extent and increased efficiency through optimal product design and production processes. Further, the aim of this strategy is also to mitigate the waste discharge and emissions through effective management of the waste generated during production, usage and recycling processes. From social and economic perspectives, this strategy strengthens the social fabric and the values interwoven in it. It also makes an attempt to change the existing conditions to mitigate the exploitation of the natural resources (Gunarathen & Lee, 2019).

Cleaner production strategy involves using cleaner, i.e., environmentally sound technology to extract natural resources, manufacture, distribute, consume, disposal of waste, and other stages of the product life cycle. This requires adopting an environmental management system capable of protecting the environment and achieving sustainability for its natural resources. Several preventive terms are used these days, such as eco-efficiency, pollution prevention, waste reduction, and waste reduction at the source. However, "cleaner production" includes them all and covers all product life cycle stages. Over the past decade, adopting cleaner production principles has helped inspire preventive thinking and spread its message worldwide. It has promoted technology, an administrative incentive, and a bridge between economic development and environmental protection to achieve sustainability for all resources (Vieira & Amaral, 2016).

2.2 Sustainable supply chain management

A sustainable supply chain management is an organizational approach that integrates environmental aspects into the supply chain structure, including traditional activities such as sourcing, logistics, manufacturing, distribution, return, reprocessing, and Recycling (Dubey et al., 2017). Sustainable supply chain is described as the process of managing the flow of raw materials, information, and money, as well as fostering collaboration between different organizations across the supply chain to achieve economic, environmental, and social goals. This approach stems from the requirements of customers and stakeholders (Gold et al., 2010). The spread of the concept is based on the premise that the environment is essential to sustainable development and quality of life. In addition, the commitment of large industrial organizations to marketing systems appears to be a necessary feature in determining the availability of suppliers and imposing obligations to protect the environment. It is noticeable that when the volume of imports and sales of goods based on the sustainable supply chain is significant, interest in the transition to a green economy increases (Seuring, 2013). The sustainable supply chain management approach focuses on environmental thinking in its supply chain activities. In an attempt to mitigate the negative environmental impact of the supply chain, the sustainable supply chain management implies multiple practices, including environmental management, green procurement, green design and production, and reverse logistics (Carter & Easton, 2011).

Humans are vital in sustainable development due to their close connection with the surrounding environment. The environment constantly interacts with its components and available natural resources, and therefore, the environment represents one of the three main factors that contribute to achieving sustainability. This is accomplished through optimal utilization and the management of natural resources to fulfil the human requirements. In this scenario, sustainable development in SCM has become a prime focus area and an established strategy for accomplishing tangible returns and achieve a competitive advantage. Further, such applications emphasize on reducing the impact on environment and also increase the supply chain performance. The conventional supply chain processes underwent a radical transformation, thanks to environmental sustainability, from chain expansion stage to its design, implementation and monitoring the SCM performance (Koberg & Longoni, 2019).

The concept behind the integration of supply chain practices and environmental sustainability is to provide an edge for the organizations by entering into partnerships so as to adopt a sustainable supply chain approach. These partnerships allow for the preservation of the environment and the saving of resources such as energy and water, in addition to improving the overall health of the community and the employees of these organizations. This effort's effects are evident in forming a new culture among consumers. Consumers base their purchasing decisions on products' potential environmental and social impact, as opposed to the services provided by manufacturing organizations (Carter & Rogers, 2011: 2008). Consumers prefer organizations that adopt organic materials and produce environmentally friendly products to achieve environmental sustainability and follow an approach to managing the environmentally friendly supply chain. This has prompted organizations to adapt their production to gain acceptance of this type of consumer society, which has recently increased (Serensson, 2007:263).

Theory suggests that sustainable supply chain management needs to be treated as an application or extension of the firm’s cleaner production strategies (Carter & Rogers, 2008; Gunarathne & Sankalpani, 2021; Mubarik et al., 2021). However, the impact of the cleaner production strategies on sustainable supply chain management has not been tested empirically. Thus, building on the conceptual premise that sustainable supply chain management practices align with and support the cleaner production strategy (Carter & Rogers, 2008), we propose the following hypothesis.

H1: Cleaner production strategy has a statistically significant direct positive effect on sustainable supply chain management practices.

2.3 Green intellectual capital

The construct of green intellectual capital was first introduced by Chen (2008) as an extension of the established concept of intellectual capital as a combination of different forms of intangible assets including skills, capabilities and knowledge (Martín-de Castro et al., 2019; Swart, 2006).

The concept of intellectual capital is based on the difference between the organization's market value over the book value. The market value expresses the organization's value if all its shares were sold in the market, while the book value refers to the value recorded in the financial statements. The difference between them is attributed to the new ideas, knowledge, and discoveries that are applied within the organization. In the era of a knowledge economy, organizations' intellectual capital is much larger than their traditional financial capital. With the expansion of the Internet and service industries, the gap between the market value and the book value of organizations is constantly increasing. Therefore, the actual value of an organization may not accurately reflect the official financial statements. Traditional accounting systems often cannot accurately estimate an organization's market value. For this reason, the estimation of the actual value of organizations has become based on the valuation of intangible resources. From the resource-based view (RBV) perspective (Barney, 1991), intellectual capital is considered to be a strategic resource that is rare, valuable and difficult to imitate, conductive to the competitive advantage of the firm (Martín-de Castro et al., 2019).

While intellectual capital is diffuse concept that encompasses a wide range of knowledge assets (Martín-de Castro et al., 2019; Petty & Guthrie, 2000), the construct of green intellectual capital emphasizes the intangible assets that relate to the environmental management and green innovation (Chen, 2008). It is the total stock of all kinds of intangible resources and assets, knowledge, capabilities, relationships, etc., about environmental protection or green innovation at the individual and organizational levels within the organization. It can be defined as cognitive skills, capabilities, understanding of experiences, information, and competencies related to environmental protection and environmental issues (Chen, 2008).

Green intellectual capital contributes mainly to the organization's success in environmental sustainability (Muhammad & Ismail, 2009). Ahangar (2011) also researched the positive impact of green intellectual capital on financial and organizational performance, which is essential in enhancing the sustainable supply chain. Green intellectual capital is the total balance of all the organization's intangible assets, knowledge, and capabilities related to environmental and sustainability issues that can create values or competitive advantages to achieve its goals. There were two types of green intellectual capital studies: intellectual capital management and intellectual capital measurement. Studies on green intellectual capital management have focused on managing intangible assets, knowledge stocks, and organization capabilities to create value or competitive advantages. In contrast, studies on green intellectual capital measurement have focused on collecting, analyzing, and evaluating non-financial information to measure organizations' intangible assets that are insufficient for financial statements (Roos & Roos, 2017). Hence, green intellectual capital disclosure can be considered supplementary information to the organization's financial statements (Edvinsson & Malone, 2007).

Following the previous classifications of intellectual capital into three components (human, structural and relational), Chen (2008) proposed three dimensions of the green intellectual capital. Green human capital includes knowledge, skills, capabilities and skills of the employees. Green structural, or organizational capital encompasses intangible assets embedded in organizations, such as organizational capabilities, culture, hardware, software and databases. Green relational, or relationship (Chang & Chen, 2012) capital reflects the firm's relationships with its partners, including customers and suppliers, and includes loyalty and trust (Chen, 2008). These definitions of different forms of green intellectual capital suggest that they represent the different levels: individual (green human capital embedded in the employees), organizational (green structural capital embedded in the organization) and the level of the external environment (green relational capital embedded in the firm's relationships with its stakeholders). While these layers and components interact and interplay (Benevene et al., 2021), the three dimensions of green intellectual capital may also be treated as separate variables (Liu et al., 2022).

Several studies have integrated the relationships between green intellectual capital and the sustainable supply chain management within the broader conceptual framework. Khan et al. (2021) explored the link between intellectual (but not green) capital and green supply chain management in the SME context, finding a statistically significant effect. Tjahjadi et al. (2023) confirmed the effect of the green human capital, one of the dimensions of green intellectual capital, on sustainable supply chain management. Liu et al. (2022) studied the effect of all three dimensions of green intellectual capital on green supply chain integration. These studies support the theoretical premise that execution of the cleaner production strategy that manifests itself in the sustainable supply chain management practices needs specific individual, organizational and stakeholder-related competences and resources that constitute green intellectual capital. Specifically, green intellectual capital can affect the link between the strategic choices and specific operations (Benevene et al., 2021), including sustainable supply chain management. Following this premise, we propose the following hypotheses on the moderating effect of green intellectual capital and its dimensions on the relationship between cleaner production strategies and sustainable supply chain management practices.

H2: Green intellectual capital significantly moderates the relationship between cleaner production strategy and sustainable supply chain management practices.

H2a: Green human capital significantly moderates the relationship between cleaner production strategy and sustainable supply chain management practices.

H2b: Green structural capital significantly moderates the relationship from Cleaner production strategy to Sustainable supply chain.

H2c: Green relational capital (green social capital) significantly moderates the relationship between cleaner production strategy and sustainable supply chain management practices.

3 Methods

3.1 Sample

The sample was collected from the Etihad Food Industries Company. Etihad Food Industries Company was established in 2012 in the Al-Madhatiyah area of Babil Governorate. The company established the first sugar refinery in Iraq, and to date, the company is the only one in Iraq specializing in sugar refining. The sugar company has 4,000 employees. The company began in 2015 with a production capacity of 3,000 tons of refined white sugar daily, gradually increasing to 4,200 tons daily.

In 2016, the Etihad Food Industries Company started vegetable oil production, which started with a production capacity of 2,000 tons per day of refined vegetable oils. The production capacity later increased to reach 2,400 tons of refined vegetable oils daily. The number of people working in the oil refining company is about 1,000. The company owns a power generation station with a capacity of 60 megawatts. The Etihad Food Industries Company also owns a large fleet of trucks for transporting sugar and oil, as it has 400 trucks for transporting sugar, 150 tanker trucks for transporting oil, and 50 multi-purpose trucks. The company also owns its dock in Umm Qasr Port in Basra, which it uses to import raw materials from abroad.

To determine the type and size of the current study sample, the researcher chose a random sample from the current study community, represented by Etihad Food Industries Company employees (sugar factory and oil factory), numbering 1100 technical and management specialists, based on the tables (Krejcie & Morgan, 1970) that define the sample individuals for a known community. The measurement instrument (questionnaire) was distributed to 285 workers in the sugar and oil factories. 280 questionnaires were returned, of which 275 questionnaires were valid for statistical analysis, so the return rate reached 98.2%. See Table 1 for the characteristics of the study sample.

Table (1) Sample characteristics

Characteristics	Category	Sugar factory	Oil factory	Total	Ratio, %
Gender	Male	700	400	1100	100
	Female	0	0	0	0
	Total	700	400	1100	100
Age	20 years and under	150	100	250	22.7
	21-30 years	300	190	490	44.5
	31-40 years	200	75	275	25
	41-50 years	50	35	85	7.7
	51 years and over	0	0	0	0
	Total	700	400	1100	100
Marital Status	Single	290	150	440	40
	Married	410	250	660	60
	Widowed	0	0	0	0
	Divorced	0	0	0	0
	Total	700	400	1100	100
Educational Attainment	Intermediate and below	200	30	230	20.9

	Preparatory	50	25	75	6.8
	Diploma	20	35	55	5
	Bachelor's	410	300	710	64.5
	Higher certificates	20	10	30	2.7
	Total	700	400	1100	100
Job Position	Head of Department	20	8	28	2.5
	Division Head	50	15	65	5.9
	Unit Head	100	30	130	11.8
	Employee	530	347	877	79.7
	Total	700	400	1100	100
Years of Service	5 years and less	300	199	499	45.3
	6-10 years	250	200	450	40.9
	11-15	150	1	151	13.7
	16-20 years	0	0	0	0
	21-25 years	0	0	0	0
	Over 25 years	0	0	0	0
	Total	700	400	1100	100

Source: Table prepared by researchers

3.2 Measures

Cleaner production strategy: The independent variable of cleaner production strategy was measured using the scale by Satyro et al. (2023). The scale measures nine dimensions of the cleaner production strategy: Strategy (2 items), Waste (3 items), Recycling (3 items) paragraph, Life cycle (2 items), Resources (2 items), Energy (2 items), Production (8 items), Work (4 items), Performance Environment (2 items).

Sustainable supply chain management practices: The dependent variable of sustainable supply chain management practices was measured using the scale based on Paulraj et al. (2017), which includes four dimensions: Sustainable product design (7 items), Sustainable process design (5 items), Sustainable design on the supply side (6 items), Sustainable design on the demand side (5 items).

Green intellectual capital: A moderating variable of green intellectual capital and its dimensions was measured using the scale based on Chen (2008). Green human capital is measured with 4 items, green structural capital is measured with 9 items, and green relational (social) capital is measured with 5 items.

The five-point Likert scale was used in all scales, ranging from the phrase "strongly disagree," which was given a weight of (1), to the phrase "strongly agree," which was given a weight of (5). The scales are shown in the Appendix.

4 Data Analysis

There is a surge experienced in the deployment of Artificial Neural Networks (ANNs) in management research, in the recent years, especially in the analysis of complex relationships among the variables. In this background, the aim of this study is to analyze the complex interplay between Sustainable Supply Chain (SSC) management practices and Cleaner Production Strategy (CPS) under the moderating effect of Green Intellectual Capital (GIC) along with its dimensions such as social or relational capital (SC), green structural capital (GSC) and green human capital (GHC). In order to analyze such a complex relationship amongst these variables, it is important to have a highly-robust analytical approach that holds the potential to capture non-linear interactions and intricate data patterns. So, the ANNs are deployed in this study methodology that helps the researcher to achieve a novel understanding about the influence of the variables among one another. The data collected for the study was analyzed using R programming (R Core Team, 2022) while the primary constructs such as the CPS, SSC and the GIC along with their dimensions were determined as a row-wise means of the corresponding survey question groups. Once the data was preprocessed, the survey data was analyzed for descriptive statistics including means, Standard Deviations (SD) and the rest of the measures for the prime variables. Further, the bivariate relationships were analyzed for the variables under study using correlation analysis. Various neural network models were developed and made use of, to understand the direct and the moderatory effect. Different performance metrics such as the R-squared, RMSE (Root Mean Square Error), MAE (Mean Absolute Error) and MSE (Mean Squared Error). To conclude, the visualization techniques were also deployed here to provide an illustration of the neural network structures and how it interact among one another. The neural network architectures were constructed as a group while an interaction plot was developed to demonstrate the moderating influence of GIC upon the CPS-SSC relationship.

4.1 Preliminary Analysis

Prior to the primary analysis, the authors performed various preliminary data screening procedures in order to ensure that the dataset is with quality and reliable. The current section briefs the initiatives taken to overcome the issues pertaining to missing data, outlier identification and the normality assumption. At first, the Expectation-Maximization (EM) algorithm was utilized to identify the missing data while this advanced imputation method was preferred to conventional methods like mean substitution or listwise deletion as this technique does not disrupt the relationships that exist among the variables when providing unbiased estimates (Roth, 1994; Little and Rubin, 2019). The EM algorithm determined the missing values iteratively on the basis of the data patterns observed in the sample in order to keep intact the underlying structure of the data.

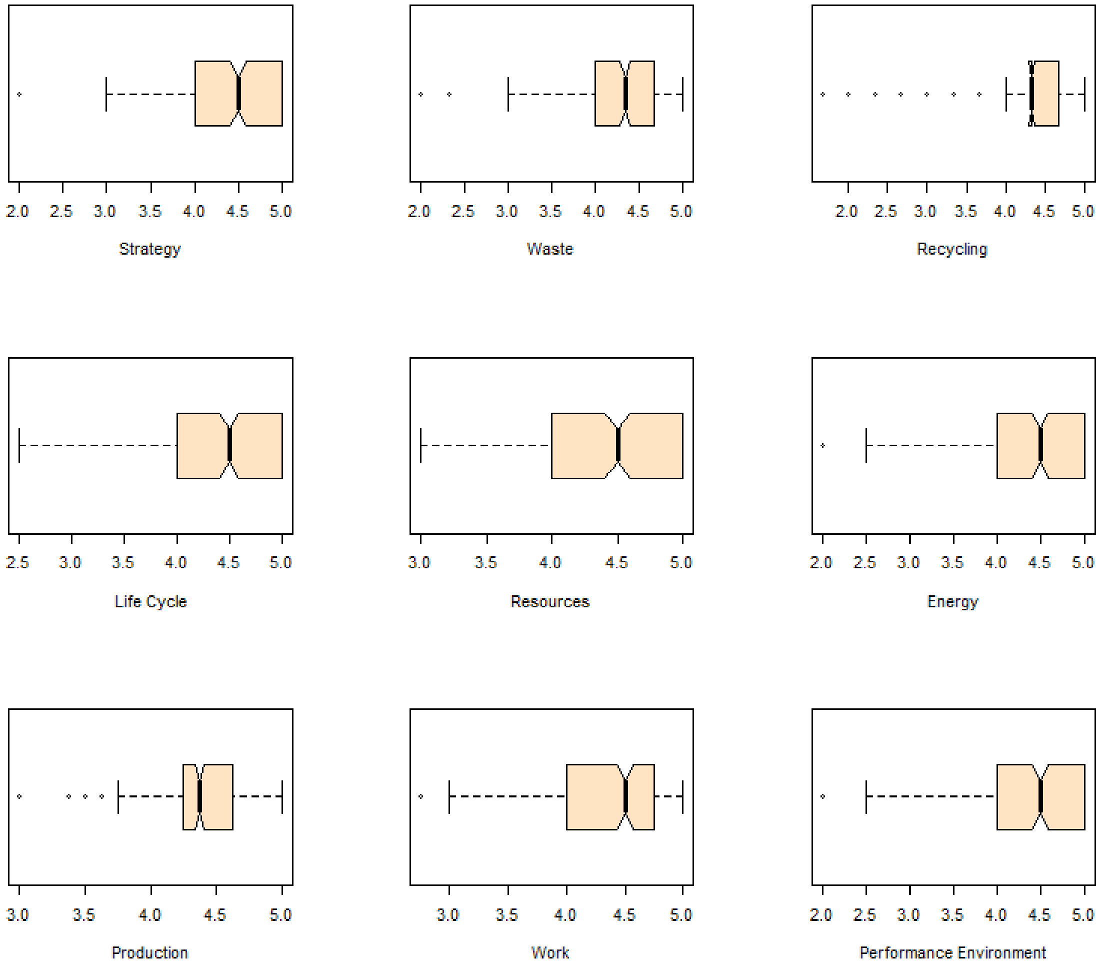

Figure (1) Outliers diagnostics for cleaner production strategy dimensions

With regards to outliers, a holistic analysis was conducted in boxplot visualization method for the entire set of study variables. The boxplots revealed that most dimensions of CPS show moderate outliers, particularly in Strategy, Waste, and Recycling variables. While Life Cycle, Resources, and Energy display relatively symmetric distributions with few mild outliers. Production, Work, and Performance Environment show similar patterns with occasional lower outliers.

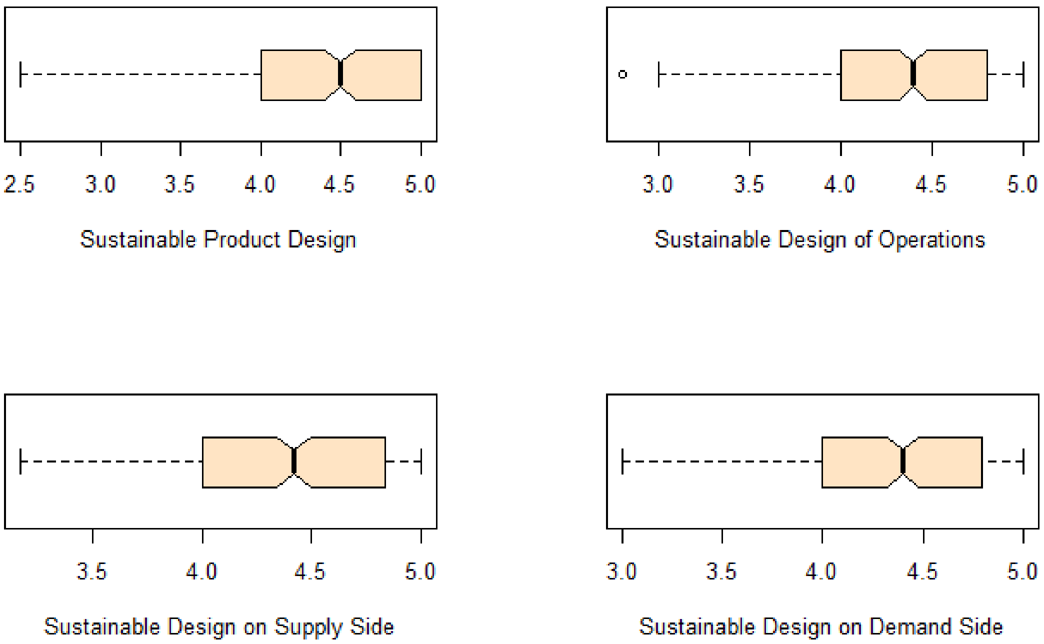

Figure (2) Outliers diagnostics for sustainable supply chain management dimensions

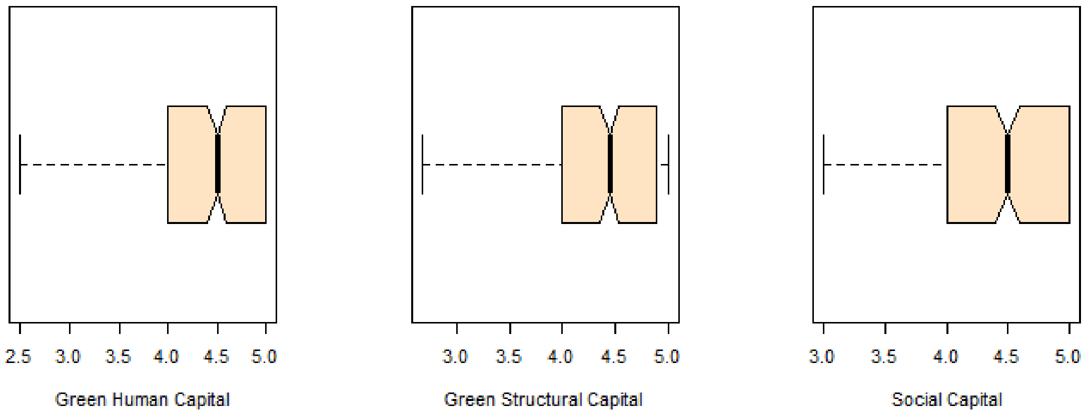

Figure (3) Outliers diagnostics for Green intellectual capital dimensions

For the SSC dimensions, the distributions appear fairly consistent across all four dimensions. For the GIC, all three dimensions (GHC, GSC and SC) show remarkably consistent distributions. Given that our subsequent analysis will employ neural networks, which are generally robust to outliers, and considering that the number of outliers identified is relatively small, we decided to retain these cases in our dataset. This decision was also supported by the fact that these outliers might represent meaningful variations in our data rather than measurement errors, particularly given the nature of our 5-point Likert scale measurements. Regarding normality, the boxplots suggest that most variables demonstrate reasonably symmetric distributions, as indicated by the relatively centered position of the median lines within the boxes.

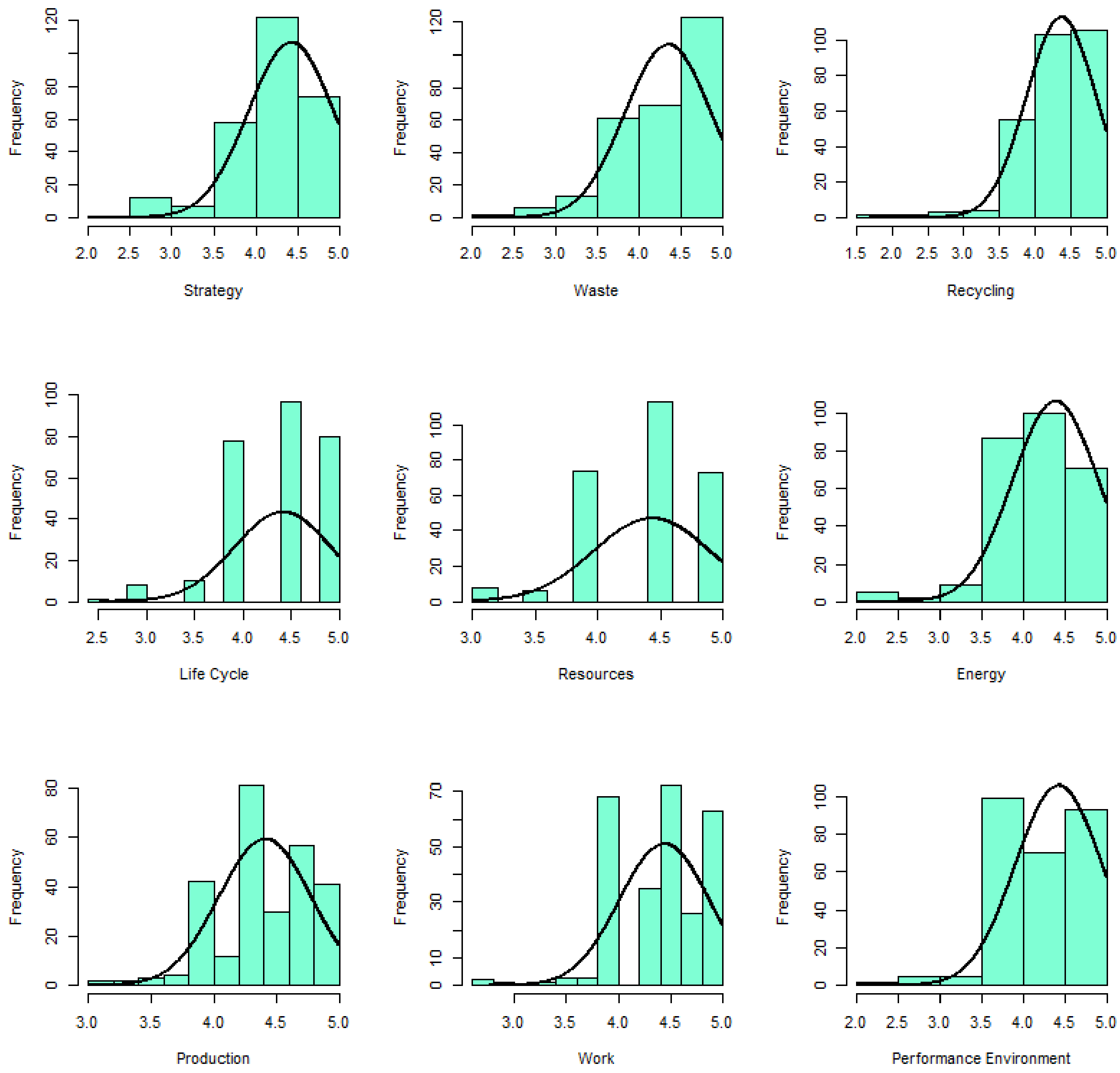

Figure (4) Normality diagnostics for cleaner production strategy dimensions

The normality assessment was conducted through visual inspection of histograms with superimposed normal curves for all study variables. While perfect normality is not a strict requirement for neural networks, understanding the distribution patterns remains valuable for data interpretation.

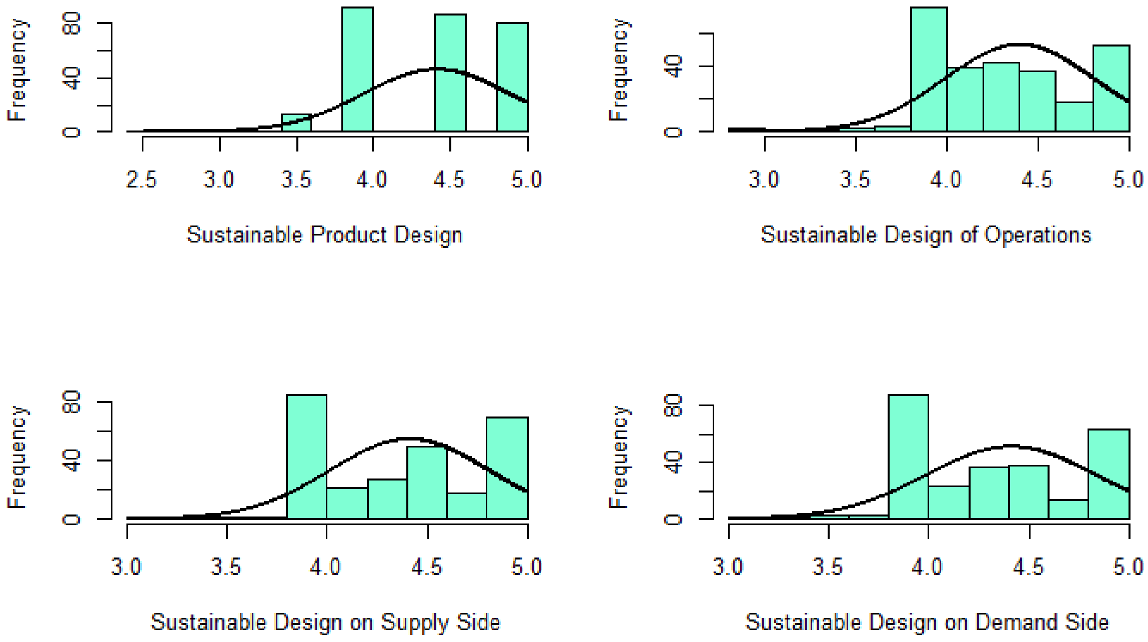

Figure (5) Normality diagnostics for Sustainable supply chain dimensions

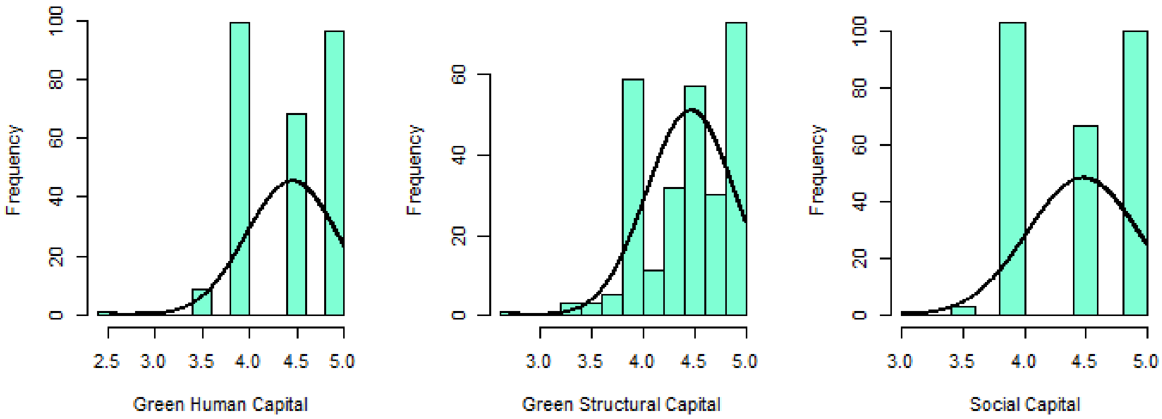

Figure (6) Normality diagnostics for Green intellectual capital dimensions

For the CPS dimensions, the histograms reveal varying distribution patterns. Strategy, Waste, and Recycling demonstrate relatively normal distributions with a slight positive skew, as evidenced by the concentration of responses in the upper range (4.0-5.0). Life Cycle and Resources show more pronounced departures from normality with a multimodal distribution, particularly visible in the peaks at 4.0, and 4.5. Energy and Performance Environment display more symmetrical distributions that closely follow the normal curve, especially in the central portions of their distributions. Examining the SSC dimensions, all four components (Product design, Operations, Supply side, and Demand side) exhibit similar distribution patterns. They show moderate departures from normality with slight bimodal tendencies, particularly noticeable in the peaks around 4.0 and 5.0. The Sustainable Product Design variable demonstrates the most pronounced bimodal pattern, while Sustainable Design of Operations shows a more evenly distributed pattern across the upper range of the scale. For the GIC dimensions, the distributions appear relatively consistent across all three components. GHC and SC display similar patterns with distinct peaks at 4.0 and 5.0, suggesting a bimodal distribution. GSC shows a more graduated distribution pattern that more closely approximates normality, though still with some positive skewness. Given that our primary analysis will employ Neural Networks, which are robust to non-normal distributions and can effectively handle complex patterns in data, these moderate departures from normality do not pose significant concerns for our subsequent analyses. Based on this preliminary analysis, we conclude that our dataset is appropriate for further analysis using Neural Networks, with no severe violations of statistical assumptions that would warrant additional data transformations or case removals.

4.2 Descriptive Statistics

Table (2) indicates that the data shows remarkably high overall scores across all variables, with means consistently above 4.3 on the 5-point Likert scale, suggesting that respondents generally reported strong implementation of sustainable practices across all dimensions. The sample size of 274 respondents provides a robust basis for statistical analysis. Looking at CPS and its dimensions, we observe that the overall strategy component has a mean of 4.429 with a relatively high standard deviation of 0.51, indicating some variability in strategic implementation. Among its dimensions, Performance Environment and Waste show the highest variability (SD = 0.52), while Production shows more consistency across responses (SD = 0.37). The lowest mean among these dimensions is found in Waste management (4.347), while Resources shows a higher mean of 4.432, suggesting that organizations might be more advanced in resource management compared to waste handling.

Table (2) Descriptive Statistics

Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Cleaner Production Strategy	274	4.407	0.3	3	4.3	4.6	5
Sustainable Supply Chain	274	4.420	0.31	3.3	4.2	4.6	5
Green Intellectual Capital	274	4.456	0.38	2.7	4.2	4.7	5
Strategy	274	4.429	0.51	2	4	5	5
Waste	274	4.347	0.52	2	4	4.7	5
Recycling	274	4.370	0.49	1.7	4.3	4.7	5
Life Cycle	274	4.416	0.5	2.5	4	5	5
Resources	274	4.432	0.47	3	4	5	5
Energy	274	4.389	0.51	2	4	5	5
Production	274	4.411	0.37	3	4.2	4.6	5
Work	274	4.441	0.43	2.8	4	4.8	5
Performance Environment	274	4.427	0.52	2	4	5	5
Sustainable Product Design	274	4.412	0.48	2.5	4	5	5
Sustainable Design of Operations	274	4.399	0.41	2.8	4	4.8	5
Sustainable Design on Supply Side	274	4.412	0.4	3.2	4	4.8	5
Sustainable Design on Demand Side	274	4.411	0.43	3	4	4.8	5
Green Human Capital	274	4.449	0.48	2.5	4	5	5
Green Structural Capital	274	4.464	0.43	2.7	4	4.9	5
Social Capital	274	4.478	0.45	3	4	5	5

Source: Table prepared by researchers

Regarding SSC and its dimensions, there is remarkable consistency in the means across all four dimensions, ranging from 4.399 to 4.412. The standard deviations are moderate, ranging from 0.40 to 0.48, indicating relatively consistent responses across the sample. Notably, both supply-side and demand-side sustainable design show similar means (4.412 and 4.411 respectively), suggesting balanced attention to both aspects of the supply chain. The GIC construct and its dimensions show some of the highest means in the dataset. SC leads with a mean of 4.478, followed by GSC at 4.464, and GHC at 4.449. These high scores, coupled with moderate standard deviations (0.43-0.48), suggest that organizations in the sample have made significant investments in their intellectual capital infrastructure, particularly in social and structural aspects.

It's worth noting that despite the generally high means, all variables show some minimum values well below the means (ranging from 1.7 to 3.3), indicating that while most organizations report high levels of implementation, there are some that lag significantly behind. However, the 25th percentile values being consistently at or above 4.0 suggest that three-quarters of the organizations in the sample report very high levels of implementation across all dimensions. The tight clustering of the 75th percentile scores (mostly between 4.6 and 5.0) further reinforces that a significant portion of organizations report near-maximum implementation of these sustainable practices, though the spread between the 25th and 75th percentiles indicates meaningful differentiation among organizations in the sample.

4.3 Correlation analysis

Correlation coeffecients are shown in Table 7. First, there is a moderate to strong positive correlation between CPS and the SSC (r = 0.52). When looking at the dimensions of CPS, several notable relationships emerge with the SSC dimensions. Production shows particularly strong correlations with the SSC dimensions, with coefficients ranging from 0.81 with overall supply chain management down to 0.40 for specific operational aspects. Work and Performance Environment also demonstrate substantial correlations with sustainable supply chain practices, showing coefficients around 0.73 and 0.57 respectively. The waste management and recycling dimensions of CPS show moderate to strong correlations (0.67 and 0.73 respectively) with sustainable supply chain practices, indicating that organizations with stronger waste management and recycling practices tend to have more robust sustainable supply chain systems.

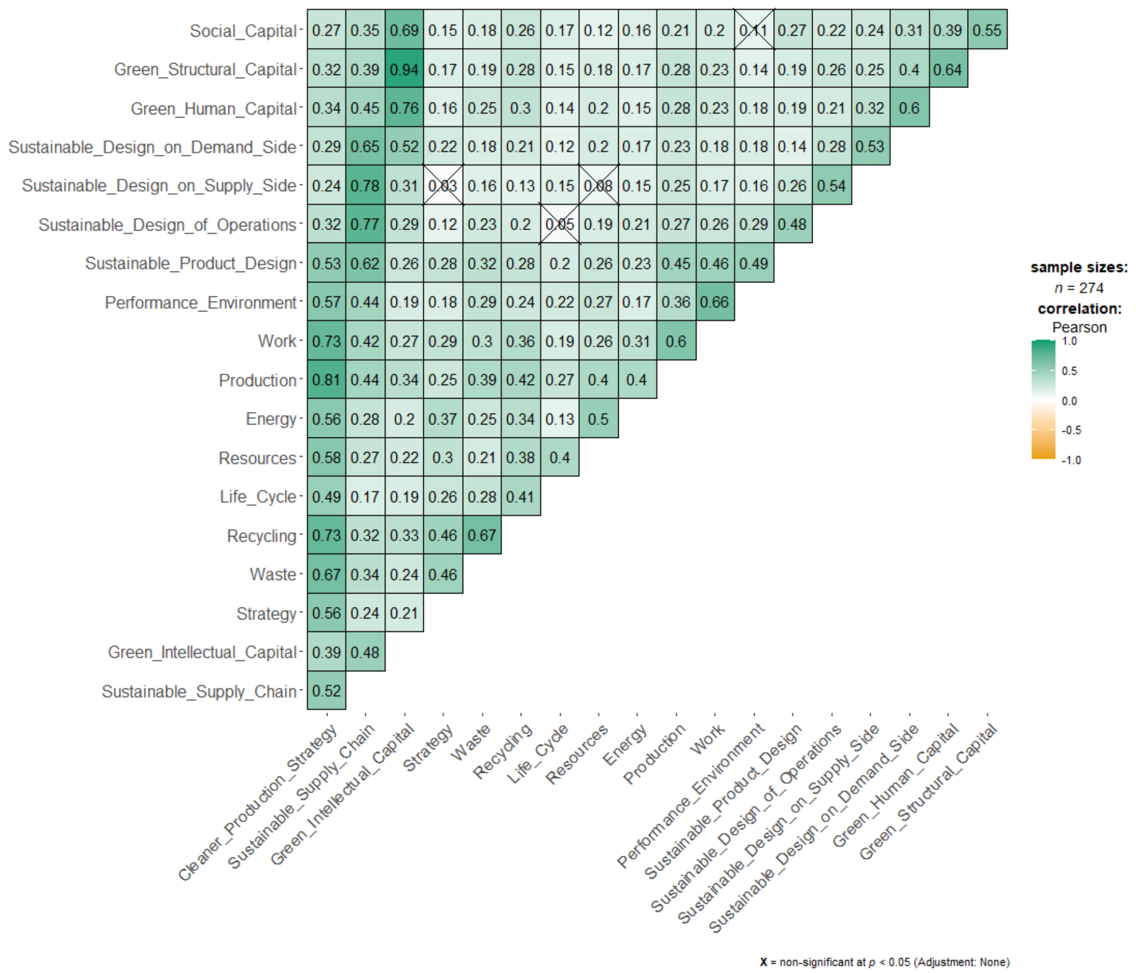

Figure (7) Visualization of correlation matrix

Regarding the relationship between GIC and SSC, the correlation analysis reveals that the overall GIC shows a moderate positive correlation (r = 0.39) with SSC. Looking at GIC dimensions, SC demonstrates the strongest relationships with SSC practices, showing correlations ranging from 0.27 to 0.55 across different SSC dimensions. GSC follows a similar pattern with correlations ranging from 0.19 to 0.64, with particularly strong relationships with sustainable design on both supply and demand sides. GHC shows moderate correlations with sustainable supply chain dimensions, with coefficients ranging from 0.19 to 0.60, suggesting that human capital development plays a significant role in supporting sustainable supply chain practices. It is worth noting that all three dimensions of GIC (Human, Structural, and Social) show stronger correlations with the demand-side and supply-side dimensions of sustainable supply chain (ranging from 0.53 to 0.64) compared to their correlations with operational aspects. This suggests that GIC might have a more pronounced influence on strategic aspects of sustainable supply chain management rather than operational elements. The correlation matrix also reveals that nearly all relationships are statistically significant (very few X marks indicating non-significance), which strengthens the reliability of these findings for our research model.

4.4 Neural network analysis

The conceptual framework of this research is grounded in the premise that CPS, encompassing various dimensions such as strategy formulation, waste reduction, and resource management, directly impacts SSC. By employing a structured approach to measure these dimensions, we can elucidate how the implementation of CPS translates into enhanced sustainability outcomes. Furthermore, the role of GIC, which comprises components such as GHC, GSC, and SC, introduces an additional layer of complexity. It is hypothesized that GIC not only influences SSC directly but also moderates the relationship between CPS and SSC, thereby amplifying the effects of cleaner production practices. An interaction term was also created by scaling and multiplying the main CPS and GIC variables. This interaction term was included to explore whether GIC moderates the relationship between CPS and SSC. This research leverages ANNs to test two primary hypotheses: first, the direct effect of CPS on SSC; and second, the moderating effect of GIC on this relationship. ANNs enable one to model these complex interactions that may not be captured by the conventional statistical methods (Meijuan, 2021).

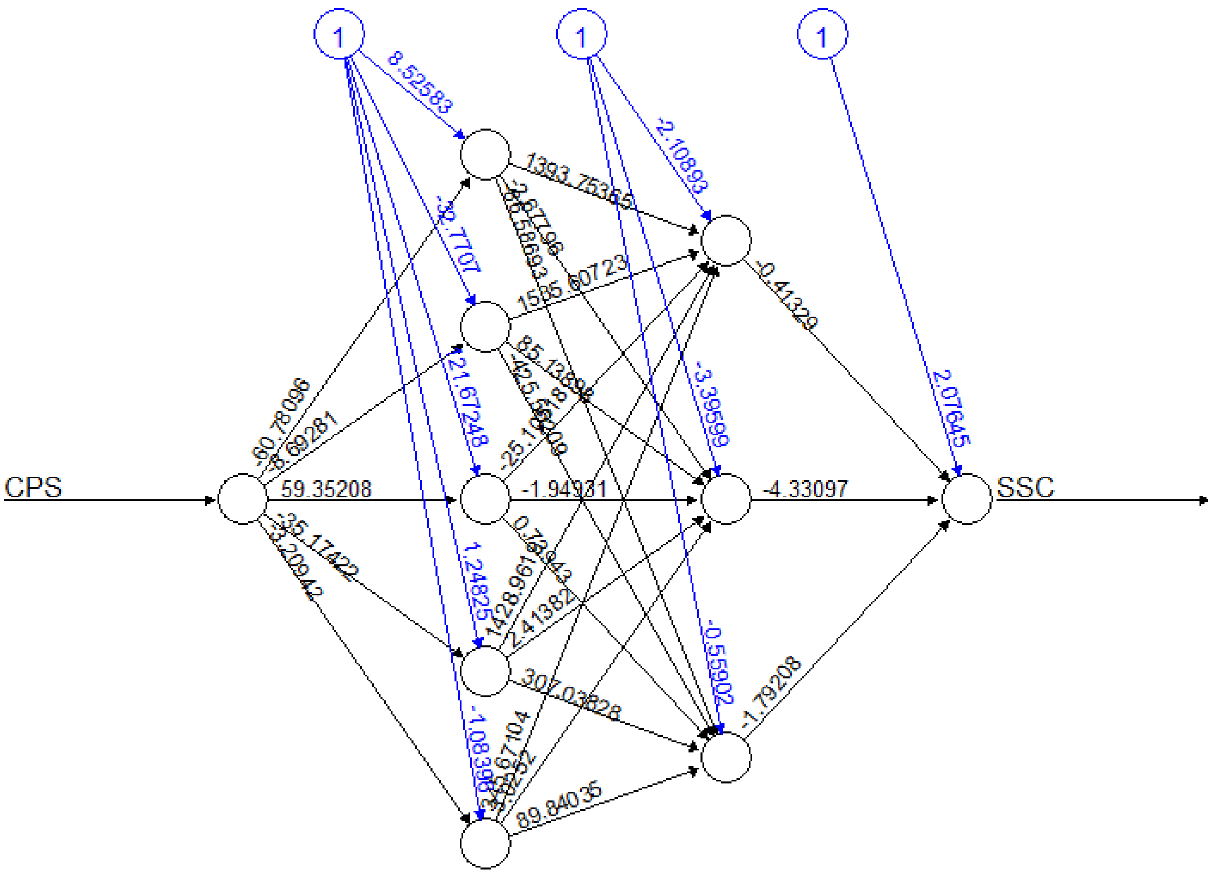

Figure (8) Neural network model for the main direct effect

Figure 8 shows the first model, a relatively simple architecture containing SSC as the output and CPS as the primary input. The model's evaluation metrics are as follows; MSE – 0.903; RMSE – 0.950; MAE – 0.756 and the R-squared value – 0.202. According to the outcomes, the CPS exerts a direct impact on the SSC though the explanatory power of the model is relatively modest. Because, the R-squared value shows that merely 20% of the variance in SSC is explained by the CPS.

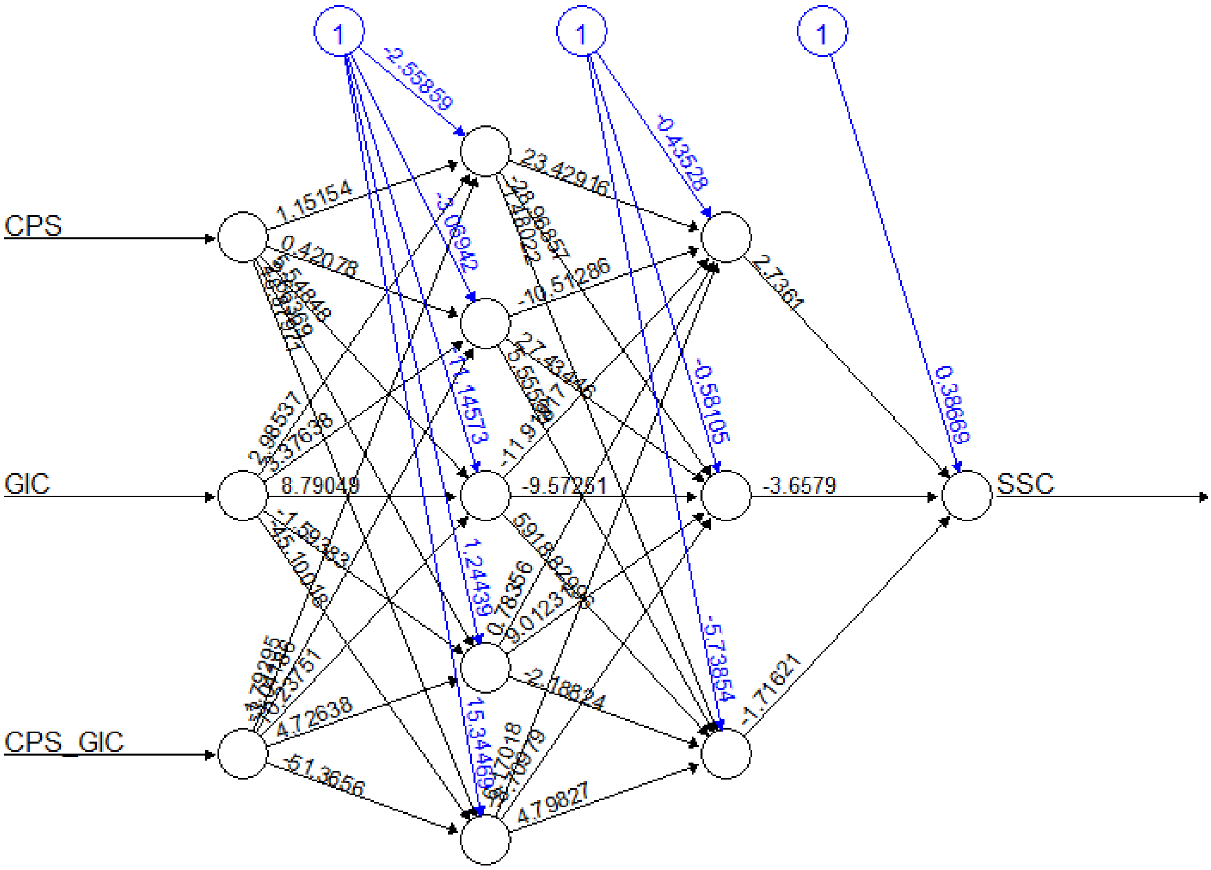

Figure (9) Neural network model for the main moderating effect

Figure 9 shows the second model in which the interaction term CPS_GIC is incorporated with the primary variables i.e., GIC and CPs. The aim of this model is to capture the moderating effect of GIC upon the relationship that exists between the SSC and the CPs. An improvement in the evaluation metrics can be understood i.e., MSE of 0.809, MAE of 0.734, RMSE of 0.8995, and an R-squared value of 0.285. The increase in the R-squared value, from 0.202 in the direct effect model to 0.285 in the moderation effect model, suggests that the inclusion of the interaction term has enhanced the model's ability to explain the variation in SSC. The improved performance of the moderation effect model indicates that the relationship between CPS and SSC is indeed influenced by the moderating role of GIC. This means that the impact of CPS on SSC is not solely direct, but is also contingent on the level of GIC. In other words, the strength of the CPS-SSC relationship may vary depending on the organization's level of green intellectual capital.

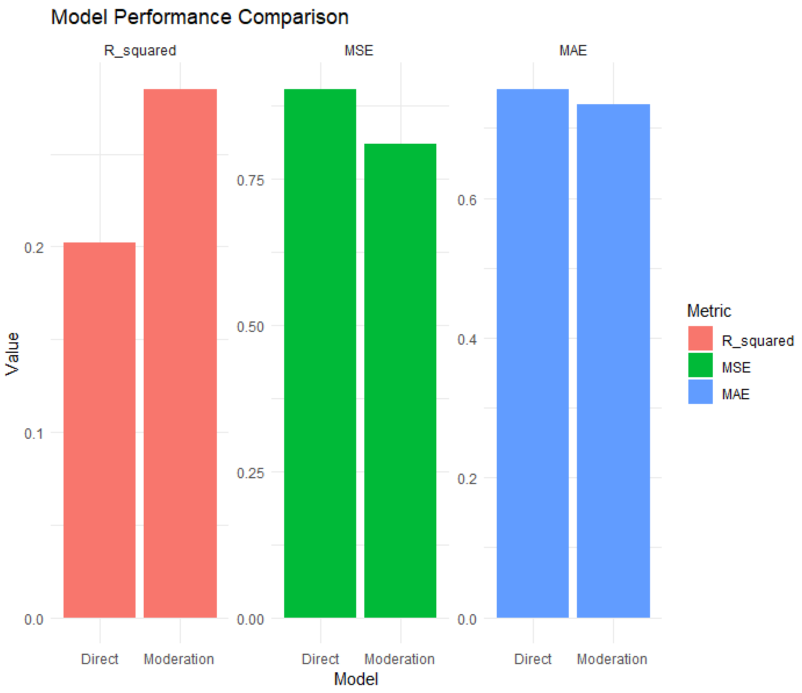

Figure (10) Evaluation metrics for the main hypotheses

The interaction plot in Figure 11 shows the relationship between CPS on the x-axis and SSC on the y-axis. The two lines depict the effect of different levels of GIC on this relationship.

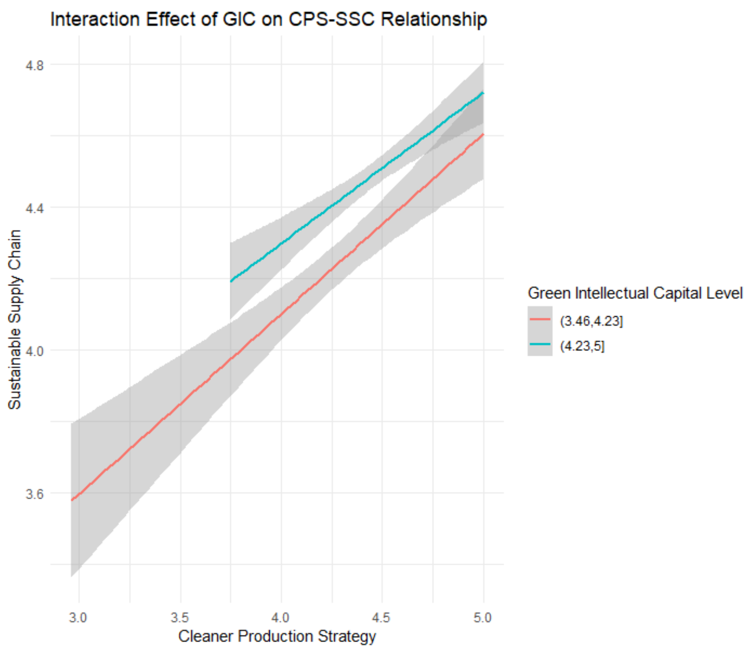

Figure (11) Interaction plot for the main moderating effect

The key observation is that the two lines, representing high and low levels of GIC, diverge as the CPS value increases. The line for high GIC has a steeper positive slope compared to the line for low GIC. This interaction plot clearly demonstrates the moderating effect of GIC on the relationship between CPS and SSC. When GIC is high, the positive impact of CPS on SSC is more pronounced. Conversely, when GIC is low, the positive relationship between CPS and SSC is weaker. The visual representation provides compelling evidence that the strength of the CPS-SSC link is contingent on the organization's level of GIC. This finding aligns with the conclusions drawn from the neural network analysis, where the moderation model exhibited improved explanatory power compared to the direct effect model.

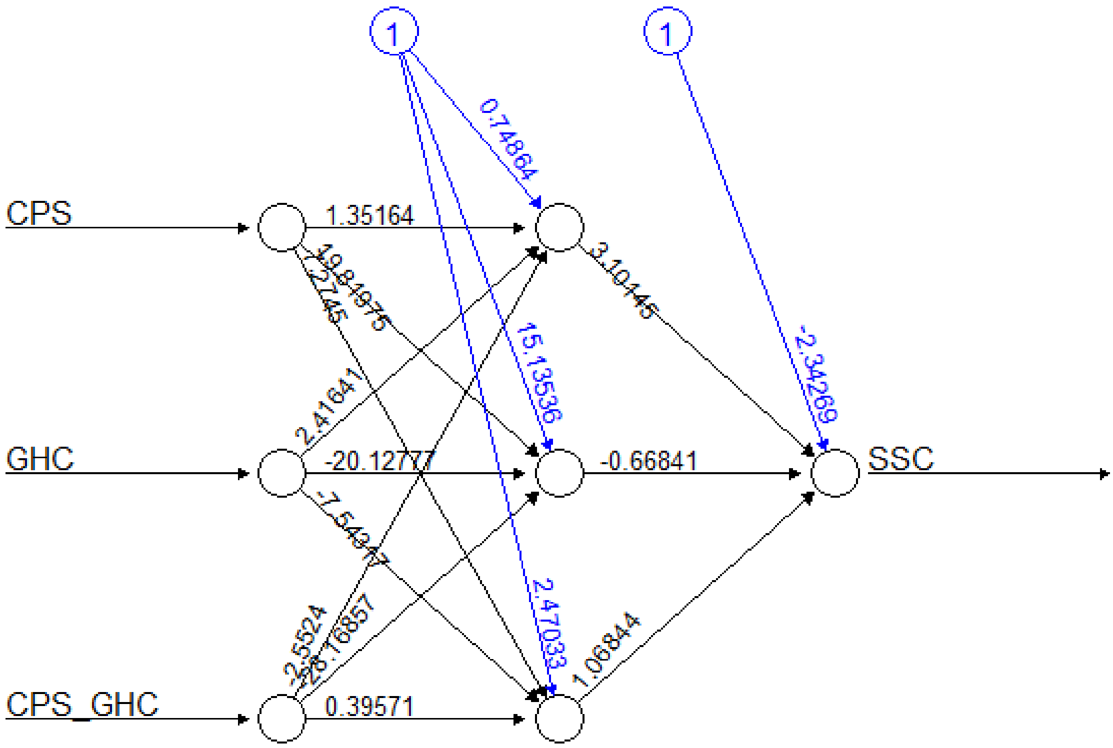

Figure (12) Neural network model for moderation effect of green human capital

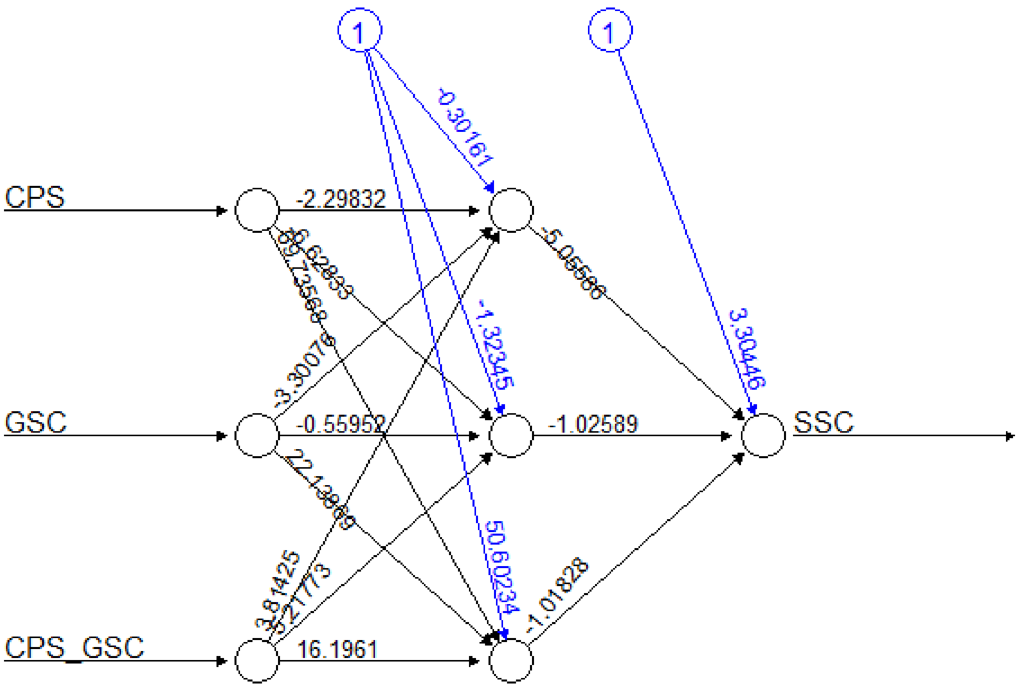

Figure (13) Neural network model for moderation effect of green structural capital

Figures 12-14 present the results for Hypotheses 2a-2c For Hypothesis 2a, which proposes the moderating effect of GHC on the relationship between CPS and SSC, the model exhibits a MSE of 0.712, a RMSE of 0.843, a MAE of 0.642, and an R-squared value of 0.371. These metrics suggest that the model can reasonably explain the relationship between the variables, with a moderate level of predictive accuracy. Hypothesis 2b, exploring the moderating effect of GSC on the CPS-SSC relationship, shows slightly higher MSE (0.753), RMSE (0.868), and MAE (0.710) values compared to Hypothesis 2a. The R-squared value of 0.335 indicates that the model has a relatively lower explanatory power compared to H2a. This suggests that the moderating effect of GSC may not be as strong as the moderating effect of GHC in this context.

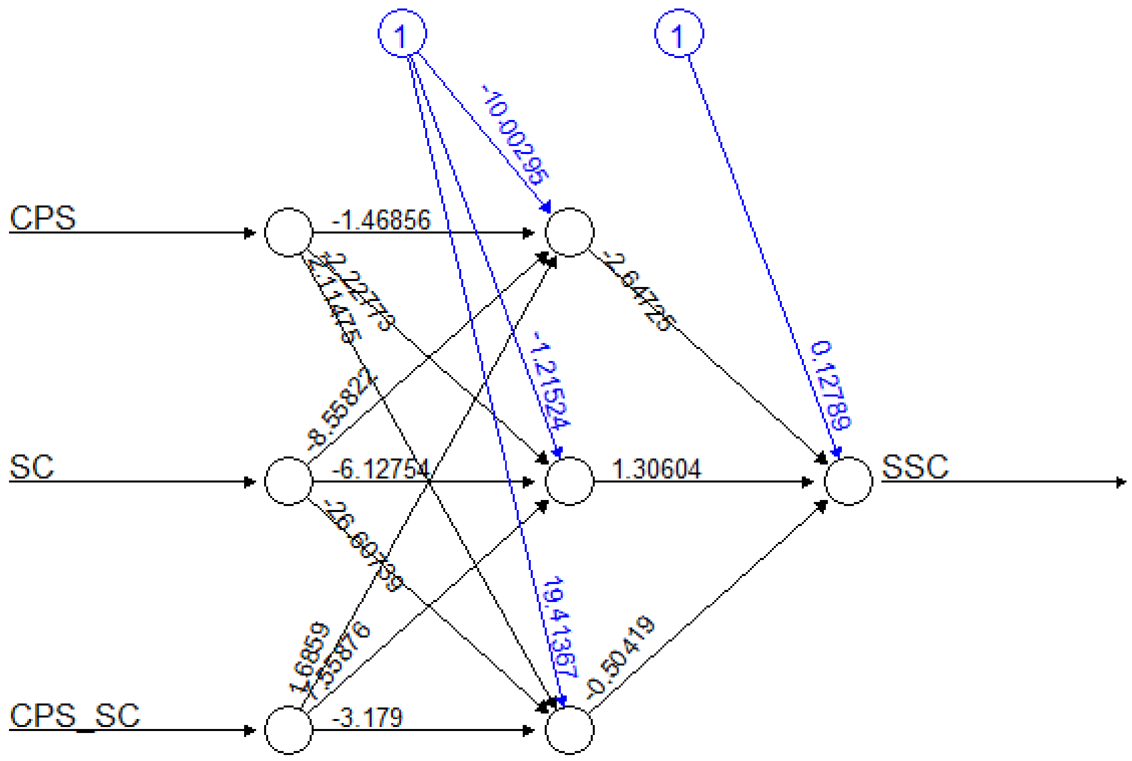

Figure (14) Neural network model for moderation effect of social capital

Hypothesis 2c recommends that the SC has a moderating role upon the CPS-SSC relationship. An improvement in the performance of the model was observed than the rest of the two hypotheses i.e., H2a and H2b. The MSE is 0.690, the RMSE is 0.831, the MAE is 0.651, and the R-squared value is 0.390. The outcomes denote that the model has the ability to explain the relationship between CPS-SSC with high accuracy and explanatory power, when taking the moderating effect of SC into consideration. On the whole, the outcomes recommend that the neural network models yield knowledgeable insights about the hypothesized relationships among which the hypothesis 2c (SC as a moderator) is the strongest performer. However, the R-squared values across all three hypotheses are relatively moderate, indicating that there may be other factors or variables that could further improve the models' ability to explain the SSC outcome.

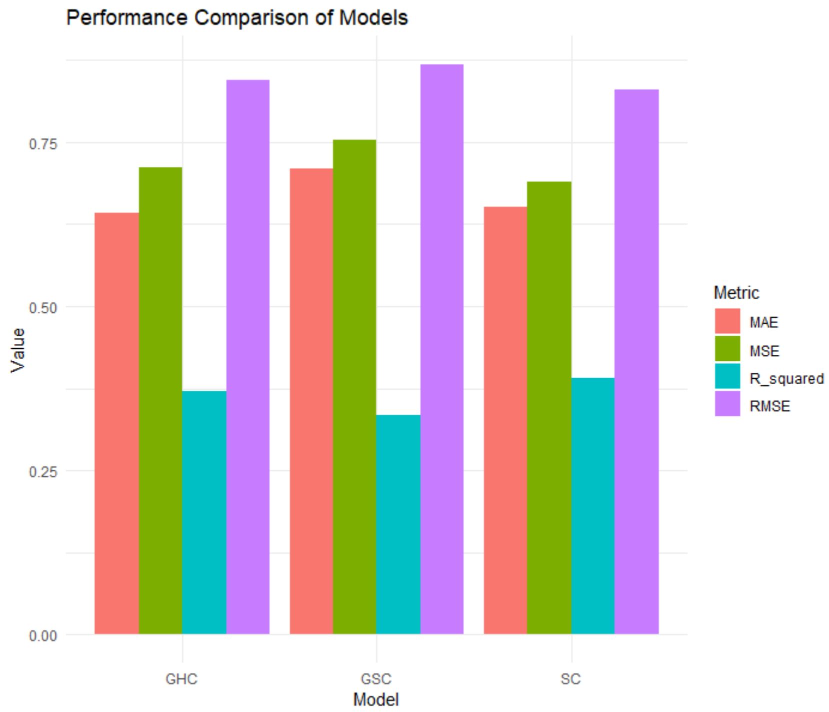

Figure (15) Evaluation Metrics for the sub-hypotheses

The GHC interaction plot in Figure 16 showed that the relationship between CPS and SSC is notably stronger when GHC is high, as evidenced by the steeper slope of the blue line. This implies that organizations with higher levels of GHC may consistently achieve better SSC outcomes across all levels of CPS implementation. This suggests that investing in employees' green knowledge, skills, and capabilities significantly enhances the effectiveness of cleaner production execution manifested in sustainable supply chain management.

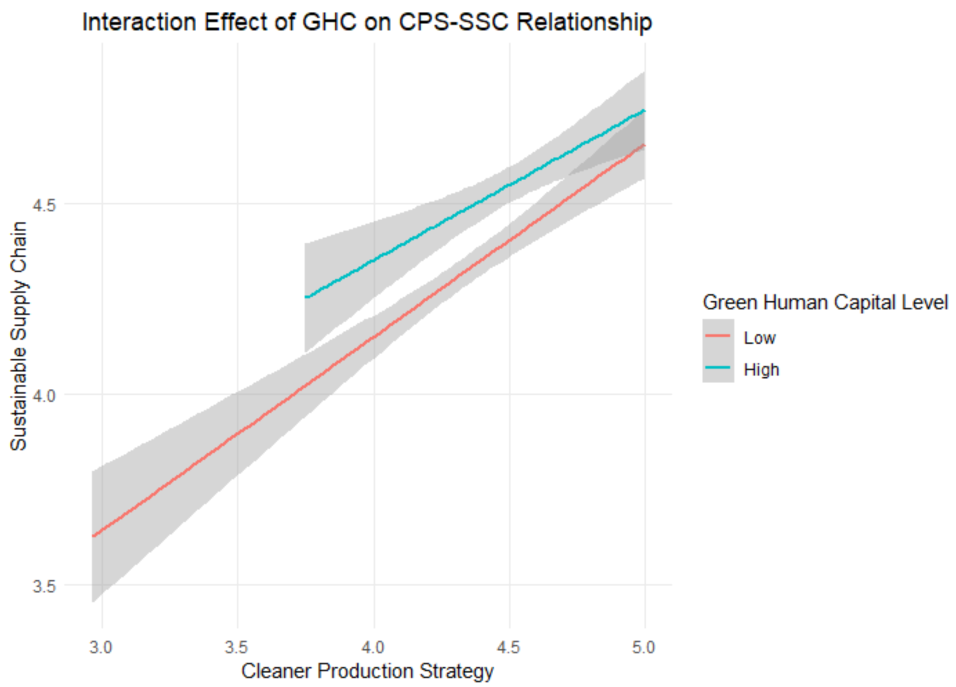

Figure (16) Interaction plot for H2a

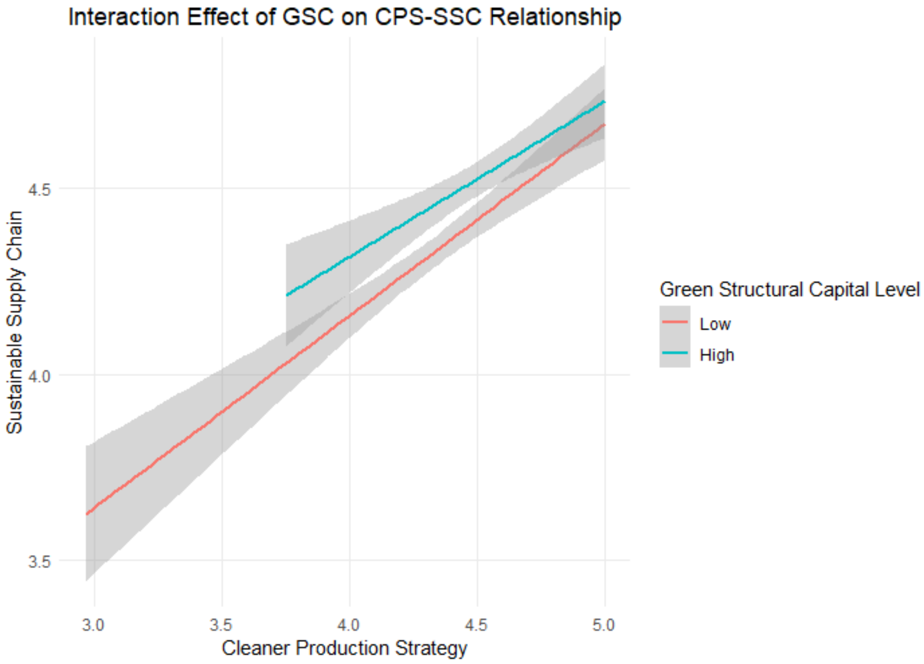

Figure (17) Interaction plot for the H2b

Figure (18) Interaction plot for the H2c

The relatively limited overlap in confidence intervals (grey shading) between high and low GHC groups further supports the strength of this moderating effect. In the case of GSC, the interaction effect follows a similar pattern but with some distinct characteristics. While higher levels of GSC (blue line) are associated with better SSC outcomes, the difference in slopes between high and low GSC groups is less pronounced compared to GHC. The greater overlap in confidence intervals suggests a more moderate effect. Interestingly, the gap between high and low GSC appears more prominent at lower levels of CPS, with some convergence as CPS increases. This implies that strong organizational green infrastructure and systems are particularly crucial when organizations are in the earlier stages of implementing cleaner production strategies. The SC interaction plot reveals a consistent but more uniform moderating effect. The parallel nature of the lines for high and low SC levels indicates that while higher SC is beneficial for SSC outcomes, its impact remains relatively stable across different levels of CPS implementation. The consistent overlap in confidence intervals throughout the CPS range suggests that SC's moderating effect, while positive, may be more subtle than that of GHC or GSC. This finding highlights the importance of strong stakeholder relationships and networks in supporting sustainable supply chain initiatives, regardless of the organization's level of cleaner production strategy implementation.

4.5 Discussion

In this research we employed the Neural network analysis to investigate the relationships between CPS, sSSC, and the moderating role of GIC. The direct effect model shows a moderate explanatory power with an R-squared value of 0.2020, indicating that CPS alone explains approximately 20.20% of the variance in SSC. The error metrics of the model i.e., MSE of 0.9029, MAE of 0.7557, and RMSE of 0.9502 shows its performance as a baseline. There was a notable improvement in the performance of the model when using GIC as a moderator. The moderation model accomplished an R-squared value of 0.2849, corresponding to the enhanced outcomes up to 8 percentage points than the direct effect model. There was also improvement observed in the error metrics as follows; increasing RMSE - 0.8995, reducing MSE - 0.892 and slightly reducing MAE – 0.7336. The outcomes infer the meaningful moderating role played by green intellectual capital in strengthening the relationship that exists between sustainable supply chain outcomes and cleaner production strategies.

When analyzing GIC dimensions further, the researcher was able to identify intriguing moderating effects. For instance, the Social, or relational capital (SC) exhibited a strong moderating effect (R-squared value - 0.3900) followed by green human capital (GHC) and green structural capital (GSC) with its R-squared values being 0.3710 and 0.3345. The error metrics was found to show similar patterns across the dimensions whereas SC accomplished the least MSE (0.6902) and RMSE (0.8308). This outcome infers that the SC is a highly effective dimension in strengthening the relationship between sustainable supply chain outcomes and cleaner production strategies. The outcomes yield critical implications, both theoretically and practically. From a theoretical perspective, this research provides empirical evidence that green intellectual capital significantly enhances the effectiveness of cleaner production strategies in achieving sustainable supply chain management practices. The higher explanatory power of the moderation models, particularly through social capital, suggests that organizations should pay special attention to developing their social capital alongside other intellectual capital dimensions.

5 Conclusion

While cleaner production strategies have a direct positive effect on sustainable supply chain performance, incorporating green intellectual capital as a moderator, particularly its social (relational) dimension, substantially enhances this relationship. The consistent improvement in model performance across different dimensions of green intellectual capital suggests that organizations should adopt a comprehensive approach to developing their green intellectual assets, mainly focusing on social (relational) capital development. Future research could explore the temporal dynamics of these relationships and investigate potential industry-specific variations in the strength of these moderating effects. Organizations looking to enhance their sustainable supply chain management practices should consider investing in their green intellectual capital, particularly in social (relational) capital that is embedded in the relations between the organization and its stakeholders, as it appears to be the most effective moderator of the relationship between cleaner production strategies and sustainable supply chain management.

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Appendix

	Independent variable: Cleaner production strategy (Satyro et al., 2023)
	First dimension: Strategy
1	Develop strategic plans to select the appropriate process that is environmentally friendly.
2	Develop strategic plans to select environmentally friendly technologies.
	Second dimension: Waste
3	Use a cleaner production strategy to reduce emissions/pollutants.
4	Use a cleaner production strategy to dispose of Waste with minimal environmental damage.
5	Use modern programs and technologies to manage Waste.
	third dimension: Recycling
6	Using a cleaner production strategy to recycle Waste
7	Digital identification of the materials that make up the products, making them easier to dispose of/reuse.
8	The organization recycles the Waste on site.
	Fourth dimension: Life cycle
9	Design to extend the life cycle of products
10	Using the cleaner production strategy to manage the life cycle of the organization's products
	Fifth Dimension: Resources
11	Using Cleaner Production Strategy to Manage Resources Efficiently
12	Using Cleaner Production Strategy to Improve Resource Use
	Sixth dimension: Energy
13	Our organization manages the renewable energy grid system
14	Our organization reuses the heat generated by the company (operations and offices)
	Seventh dimension: Production
15	Using a cleaner production strategy to manage/map the supply chain
16	Using a cleaner production strategy to manage Production efficiently
17	Using a cleaner production strategy to control inventory of work-in-process and finished products.
18	Using a cleaner production strategy to manage Production and maintenance through energy consumption.
19	A cleaner production strategy will be used to enable the integration of the production system.
20	A cleaner production strategy will be used to enable the integration of Production across the organization.
21	Using a cleaner production strategy to improve production planning and control.
22	Using a cleaner production strategy to optimize the use of human resources.
	Eighth Dimension: Work
23	Using a cleaner production strategy to improve workplace safety.
24	Using a cleaner production strategy to improve collaborative Work.
25	Using a cleaner production strategy to improve knowledge sharing.

26	Using a cleaner production strategy to improve workplace conditions.
	Ninth Dimension: Performance Environment
27	Using a cleaner production strategy to engage all stakeholders to improve organizational performance.
28	Using a cleaner production strategy to improve environmental management efficiency.
	Dependent variable: Sustainable supply chain management practices (Paulraj et al., 2017)
	First dimension: Sustainable product design
29	When designing products, we pay attention to reducing material/energy consumption.
30	We pay attention to reusing, Recycling, and recovering materials when designing products.
31	We design our products to use environmentally friendly materials.
32	We design our products with standardized components for easy reuse.
33	We design our products for easy disassembly.
34	We use life cycle analysis to evaluate the environmental impacts of our products.
35	We have formal guidelines for designing environmentally friendly products.
	Second dimension: Sustainable design of operations
36	Our process design is heavily based on sustainability goals.
37	We evaluate our current processes to minimize their impact on the environment.
38	We have a formal design of environmental guidelines for process design.
39	We are constantly re-engineering our processes to reduce their environmental impact.
40	We are working to improve the environmental friendliness of our Production.
	Third dimension: Sustainable design on the supply side
41	We collaborate with our suppliers to achieve our sustainability goals.
42	We provide our suppliers with sustainability requirements for their operations.
43	We collaborate with suppliers to provide products and/or services supporting our sustainability goals.
44	We develop a mutual understanding of responsibilities related to sustainability performance with our suppliers.
45	We conduct joint planning to anticipate and resolve sustainability issues with our suppliers.
46	We periodically provide suppliers with feedback on their sustainability performance.
	Fourth dimension: Sustainable design on the demand side
47	We collaborate with our customers to achieve sustainability goals.
48	We collaborate with our customers to improve their sustainability initiatives.
49	We collaborate with our customers to deliver products and/or services that support our sustainability goals.
50	We develop a mutual understanding of sustainability performance responsibilities with our customers.
51	We conduct joint planning to anticipate and resolve sustainability issues with our customers.
	Moderating variable: Green intellectual capital (Chen, 2008)
52	**First Dimension: Green human capital**
53	The productivity and contribution of the company's environmental protection workers are better than that of its major competitors.
54	The efficiency of the company's environmental protection employees is better than that of its major competitors.
55	The quality of the company's employees' environmental protection products or services is better than that of its major competitors.
56	The degree of cooperation in teamwork on environmental protection in the company is greater than that of its major competitors.
	Second dimension: green structural capital
57	The company's environmental protection management system is superior to its major competitors.
58	The company's environmental protection-related innovations are greater than its major competitors.
59	The profits earned from the company's environmental protection activities are greater than those of its major competitors.
60	The ratio of investment in environmental protection-related R&D expenditures of the company to its sales is greater than that of its major competitors.
61	The ratio of employees in environmental management to the company's total employees is greater than that of its major competitors.
62	The company's investment in environmental protection facilities is more significant than that

	of its major competitors.
63	The company's green product development efficiency is better than its major competitors.
64	The company's overall environmental protection operations are running smoothly.
65	The company's environmental management knowledge management system is suitable for accumulating and sharing environmental knowledge.
	Third Dimension: Relational or social capital
66	For a company that designs its products or services following the environmental desires of its customers.
67	The customer satisfaction regarding the company's environmental protection is better than that of its main competitors' customers.
68	The company's environmental protection-related cooperative relations with its suppliers in the initial stages are stable.
69	The company's environmental protection-related cooperative relations with its customers or downstream channels are stable.
70	The company has stable and good environmental protection-related cooperative relations with its strategic partners.