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Harnessing Block chain and Green Structural Capital for Environmental Sustainability: Evidence from Digitally Enabled CPEC Supply Chains

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ABSTRACT

This study investigates how green structural capital (GSC) and block chain technology (BT) contribute to sustainable environmental performance (SEP) within the context of CPEC supply chains, while considering the moderating role of digital supply chain performance (DSCP). Grounded in the technology organization environment (TOE) framework, the research employs a two-wave, time-lagged survey design across four major Pakistani cities. Using structural equation modeling, results reveal that GSC significantly enhances SEP, with BT serving as a key mediating mechanism. Furthermore, DSCP strengthens the positive effect of BT on SEP, indicating a complementary relationship between digital infrastructure and technological innovation. These findings offer theoretical advancement by integrating organizational and technological drivers of sustainability, and practical guidance for firms and policymakers seeking to align environmental objectives with digital transformation. The study underscores the importance of embedding green capabilities and block chain within digitally mature supply chains for long-term sustainable growth.

Keywords: *Green Structural Capital (GSC); Block chain Technology (BT); Sustainable Environmental Performance (SEP); Digital Supply Chain Performance (DSCP); Technology–Organization–Environment (TOE) Framework; CPEC Supply Chains; Technological Innovation; Digital Transformation; Mediation; Moderation; Sustainability; Pakistan.*

INTRODUCTION

The integration of sustainability and advanced technologies into supply chains has become an imperative for modern economies seeking competitive advantage while addressing environmental challenges. In large scale infrastructure initiatives like the China Pakistan economic corridor (CPEC), the environmental footprint of logistics, transportation, and industrial development has raised serious concerns regarding ecological degradation, waste management, and regulatory inefficiencies (Waheed et al., 2025). As supply chain become more and more digitized globally, leveraging groundbreaking technologies such as artificial intelligence as well as blockchain both offers promising pathways to enhance performance, transparency as well as environmental accountability (Chen & Guo, 2025).

A considerable body of existing literature points out the increasing popularity of sustainable supply chain management but fails to contextualize environmental practices without placing them in the broader framework of organizational capabilities, in particular green structural capital (Alsaoudi et al., 2025). At the same time, despite the interest in blockchain technology in relation to optimizing traceability and trust, little is understood about its particular mediating ability to translate green capabilities into sustainable environmental performance (Ali et al., 2025; Delgado et al., 2025). Similar to the relationship between the digital supply chain performance and these variables, there is also a paucity of empirical clarity, especially in high impact projects like the China Pakistan economic corridor (CPEC) (A. Patrucco et al., 2025; A. S. Patrucco et al., n.d.).

Recent research has outlined major shortcomings in understanding the co-existence of the green structural assets and the emergent digital technologies and their synergistic impact on sustainability in complex and large-scale economic corridors (Alavi-Borazjani et al., 2025). To achieve this necessity, this paper proposes an integrated model of analysing (1) how green structural capital influence the environment performance (2) the mediating role of blockchain technology and (3) the moderating role of the digital supply chain performance in the CPEC. The findings offer a technology integrated outlook that adds to the sustainable supply chain debate in the developing economies.

Theoretical Framing

The current study uses the technology organization environment (TOE) framework as its theoretical basis, thus giving a complete platform to the study of innovation adoption and its influence in businesses. TOE asserts that all these factors, which are the union between technological potentials of an organisation, intra-organisational as well as organisational structures and external environmental forces, define innovation driven results (Ahmed, 2020). Green structural capital (GSC) in the present study is a measure of the organisation part that entails systems, processes, and knowledge infrastructure installed through which sustainability becomes part of strategic intent (Amores-Salvadó et al., 2021). In parallel with GSC, blockchain technology (BT) is determined the technological aspect, which is characterised by its ability to foster the transparency, traceability, and secure data exchange through supply chains (Wu et al., 2025).

The environmental context is operationalized with the help of sustainable environmental performance (SEP), which is an important outcome of the emerging economy where regulatory and social pressures to clean up operations are intensified (Laguir et al., 2025). At the same time, digital supply chain performance (DSCP) represents the technological setting where the element of technological context serves as the contextual booster thus being able to increase the efficiency of blockchain technologies implemented in the supply chain (Alquraish, 2025).

The current research utilizes the TOE as a conceptual tool to test four related hypotheses that explain both mediated and direct relationship between green capabilities as well as environmental outcomes at the same time examine the moderating influence of digital performance. The TOE framework provides the necessary theoretical integrity to shine a light on the convergence of organizational preparedness and digital transformation on the impact of sustainability in the complex and infrastructure intensive environment CPEC.

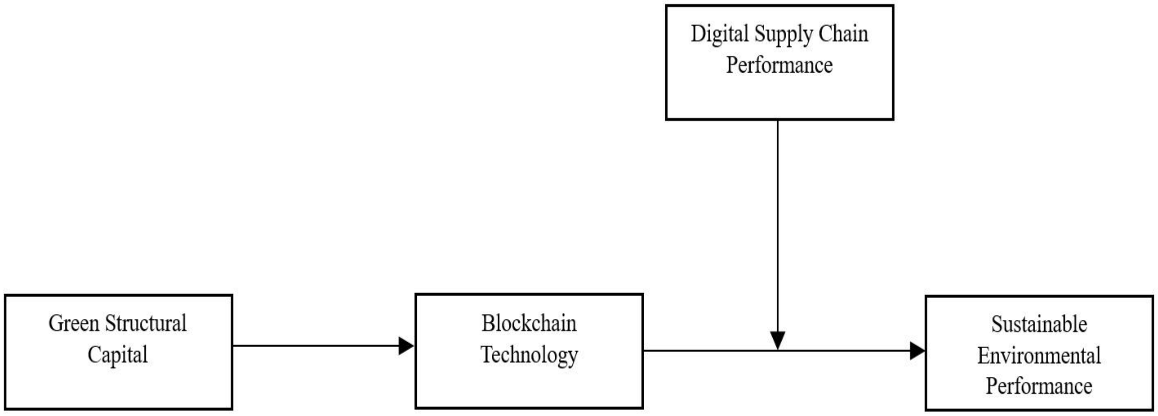

Figure 1. Theoretical model

Hypothesis Development

GSC is defined as the collective set of embedded systems, environmental processes and organizational infrastructure that directly or indirectly help the sustainability efforts (Zhu et al., 2005). High GSC companies are known to develop the environmental management system, invest capital in building up green capabilities, and instituting knowledge sharing mechanisms, so as to internalize the ecological values (Nazir et al., 2024). This type of practice allows companies to respond proactively and consistently to issues affecting the environment thus making it easy to achieve high SEP. Therefore, the argument states that:

H:1 GSC has a significant direct impact on SEP

Within the technologically dynamic setting, firms with a strong structural capital have greater chances of utilising the evolving digital innovation (Shatila et al., 2025). BT used as a enabler of supply chain, requires institutional readiness, system merger and a knowledge-based culture-feature that is regarded as typical of the intellectual infrastructure of the generic stead-state firm GSC (Yang et al., 2025). So, the GSC model will also push the adoption of BT.

Thus, the argument states that:

H2: GSC positively influences BT.

Once adopted, blockchain facilitates enhanced traceability, transparency, and data immutability factors critical for managing environmental risk, ensuring compliance, and driving sustainability outcomes (Mehmood et al., 2024). Hence, BT serves as a mechanism through which GSC translates into superior environmental performance, suggesting:

H3: BT mediates the relationship between GSC and SEP.

However, the effectiveness of blockchain in driving SEP may be contingent on broader technological capabilities. Firms with high DSCP are better equipped to leverage blockchain for real-time monitoring, decision-making, and integration with AI or big data systems (Zamani et al., 2023). This synergy can significantly enhance environmental outcomes. Thus, the impact of BT on SEP is likely to be stronger in firms with advanced DSCP:

H4: DSCP moderates the relationship between BT and SEP, such that the positive relationship is stronger with higher levels of DSCP.

RESEARCH METHODOLOGY

This study adopts a quantitative, cross sectional survey design to examine the relationships among green structural capital, blockchain technology, digital supply chain performance, and sustainable environmental performance in the context of CPEC related supply chains. A structured questionnaire was developed using measurement scales adopted from previously validated studies to ensure content validity and reliability. Items were measured on a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree").

Data were collected using a two-wave, time-lagged approach to reduce common method bias and strengthen causal inference. In Wave 1 (March 2025), data on the independent variable GSC adopted from (Tekala et al., 2024) and the dependent variable SEP adopted from (Rashid et al., 2024) were collected. In Wave 2 (May 2025), responses were gathered for the mediator BT adopted from (Gupta et al., 2023) and moderator DSCP (Al-khatib et al., 2024). This sequential design allowed temporal separation of variables.

A paper and pencil method were employed using a snowball sampling technique, targeting professionals directly involved in CPEC supply chains (Tuan, 2022). Appropriate respondents included supply chain managers, environmental officers, IT managers, logistics coordinators, and project engineers. Initial contacts were made through industry forums, university networks, and local chambers of commerce.

Data collection was conducted across four key industrial and logistics hubs: Multan, Lahore, Islamabad, and Faisalabad. These cities were selected based on their strategic involvement in CPEC eastern corridor and their concentration of relevant firms. This multi-site approach enhances generalizability within the CPEC operational context. After data screening and validation, the final dataset was subjected to structural equation modelling to test the hypothesized relationships.

Data Analysis

To assess the measurement model, reliability and validity were evaluated using multiple criteria (Hair et al., 2021). As shown in Table 1, all constructs demonstrated acceptable internal consistency. Cronbach's alpha (α) values ranged from 0.738 to 0.836, while composite reliability (CR) scores exceeded the threshold of 0.70, confirming construct reliability. Average variance extracted (AVE) values were also above the recommended 0.50 threshold, supporting convergent validity.

Construct	Items	Loadings	αlpha	CR	AVE	VIF
Block chain technology	BT1	0.760	0.836	0.879	0.549	1.737
	BT2	0.732				1.828
	BT3	0.783				2.091
	BT4	0.679				1.527
	BT5	0.790				2.240

BT6	0.695				1.771
DSCP1	0.700	0.739	0.857	0.546	1.449
DSCP2	0.750				1.587
DSCP3	0.707				1.561
DSCP4	0.806				1.819
DSCP5	0.728				1.596
GSC1	0.797	0.822	0.875	0.584	1.981
GSC2	0.743				1.752
GSC3	0.692				1.377
GSC4	0.807				1.847
GSC5	0.776				1.537
SP1	0.811	0.738	0.831	0.559	1.629
SP2	0.840				1.807
SP3	0.501				1.266
SP4	0.788				1.546

Note: CR, composite reliability; AVE, average variance extracted; αlpha, Cronbach's Alpha, VIF; collinearity statistics.

Table 1. Reliability and validity analysis

Outer loadings of items mostly exceeded 0.70, except for a few marginally lower values (e.g., SP3 = 0.501), which were retained based on overall construct reliability (Hair et al., 2017). Variance inflation factor (VIF) values ranged from 1.266 to 2.240, well below the critical threshold of 3.3, indicating no significant multicollinearity issues. Figure 1 presents the measurement model confirming item loadings and construct paths.

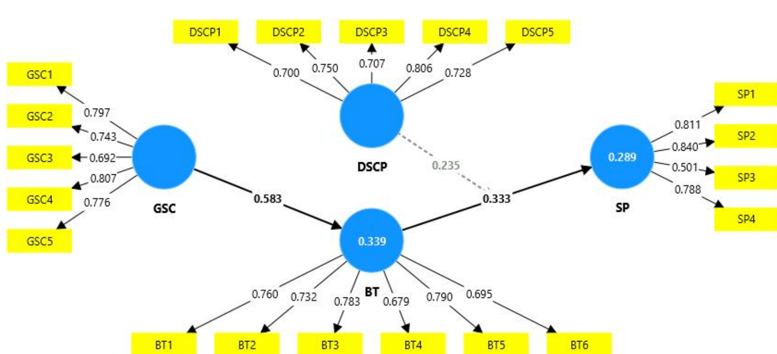

Fig 2. Measurement model

Discriminant validity was confirmed using the HTMT criterion (see Table 2). All inter construct HTMT ratios were below 0.85, satisfying the conservative threshold. Constructs were thus statistically distinct from one another (Ab Hamid et al., 2017).

Table 2. HTMT discriminant validity.

Constructs	BT	DSCP	GSC	SP
BT				
DSCP	0.568			
GSC	0.671	0.501		
SP	0.484	0.524	0.265	
DSCP x BT	0.337	0.357	0.3	0.055

For the structural model, path coefficients, t-values, and p-values were evaluated using bootstrapping (5,000 samples) (Jr et al., 2014). As shown in Table 3, all hypothesized paths were statistically significant.

Table 3 Hypotheses results.

Hypotheses	β	SD	t	P-value	Q2	R2	Results
BT -> SP	0.333	0.08	4.187	0	0.308	0.339	Supported
DSCP -> SP	0.338	0.084	4.031	0	0.197	0.289	Supported
GSC -> BT	0.583	0.066	8.846	0			Supported
DSCP x BT -> SP	0.235	0.09	2.607	0.009			Supported

Note: β, beta coefficient; SD, standard deviation; t, t-stat; P, p-value; Q2, Q-square value, R2, R-square value

GSC significantly influenced BT (β = 0.583, t = 8.846, p < 0.001), supporting H2. BT had a positive effect on SP (β = 0.333, t = 4.187, p < 0.001), and DSCP also directly influenced SP (β = 0.338, t = 4.031, p < 0.001), supporting H1 and the direct path from DSCP. The interaction term (DSCP × BT) was also significant (β = 0.235, t = 2.607, p = 0.009), confirming H4. These results indicate that DSCP positively moderates the BT-SP relationship. Figure 2 illustrates the structural model with significant paths.

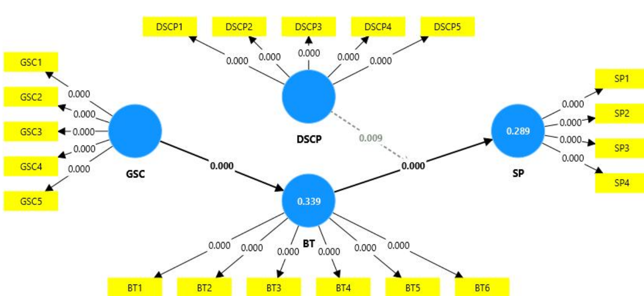

Fig. 2. Structural model

Predictive relevance (Q^2) values were above 0.15 for all endogenous constructs, and R^2 values indicated moderate explanatory power for SP ($R^2 = 0.339$) and DSCP ($R^2 = 0.289$) (see Table 3). Figure 3 displays a simple slope analysis that visually confirms the moderating effect of DSCP on the BT-SP relationship.

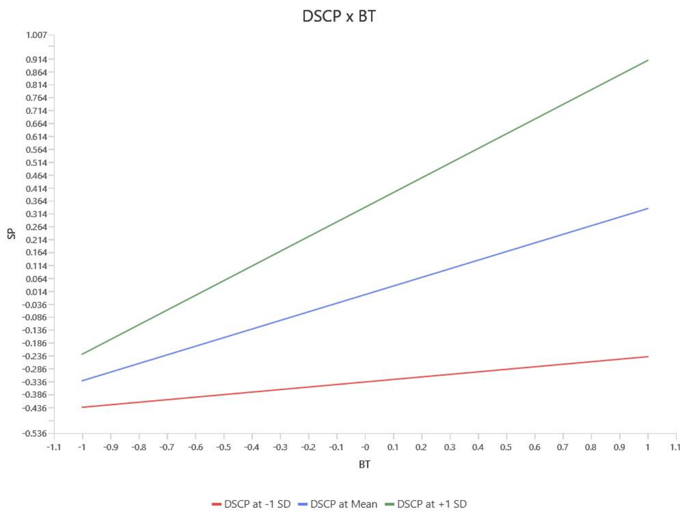

Fig. 3 Simple slope analysis

Overall, the results provide strong empirical support for the proposed model and hypotheses, validating the mediating role of blockchain and the amplifying effect of digital supply chain performance on environmental sustainability outcomes.

DISCUSSION

The findings offer compelling insights into how firms operating within CPEC linked supply chains can enhance environmental sustainability through a combination of organizational capability and technological innovation. The influence of the GSC on SEP supports the importance of institutionalizing environmental processes, systems and knowledge infrastructure. This states that green practices must go beyond amenability, entrenching into organizational DNA of firms engaged in high impact initiatives of infrastructure like CPEC.

Such evidence has shown that blockchain technology can serve as a critical intermediary to show the potential to reinforce transparency, traceability, and operational integrity in the implementation of sustainability practice. In that blockchain can serve as the technological channel between the declaratory greenness and the quantified impact on the environment, it is a decisive facilitator. Besides, the modulation effect depicts the evenness of the movement of blockchain since organizations with advanced digital supply chains realize much enhanced gains.

These findings provide a suggestion to policymakers and companies working in CPEC regarding the need to make irreproachable investment in environmental capabilities and digital ecosystems. Blockchain will require a certain degree of organizational readiness to truly make a difference, and if not made in isolation by attempting to enact implementation without a corresponding attempt to build up internal readiness, then making blockchain implementation an agent of change might instead be surrendering its effectiveness. Yet, the combination of strengthened green structural capital with the strategy of modernizing digital supply chains also makes it a potential source of synergies. Put together, the outcomes suggest an increasingly integrative policy and management direction where environmental efforts therefore intersect with development of digital infrastructure to support sustainable infrastructure development through CPEC.

Implications

The study enhances TOE which requires investigation of the means by which GSC and BT can cooperate to shape environmental performance within large scale infrastructure ecosystems. In an attempt to explain the synergetic agreements between internal abilities and external technologies in achieving sustainable results. Similarly, in terms of its practical use, the results provide viable guidance to managers and policymakers involved in the projects related to CPEC. To the manager, it is not only ethical to allocate its resources towards green systems, knowledge sharing platform as well as environment friendly processes but also a strategically beneficial practice. The implementation of a blockchain ought to be considered as a performance boosting tool that depends on the readiness of the firm in terms of its digitization. The policymakers ought to establish incentives and regulatory systems that encourage green capability building as well as digital transformation. The sustainable innovation can be jump started by encouraging the public private partnerships, availing blockchain sandboxes, and integrating environmental performance indicators into procurement. In the end the study suggests an organized collaboration between organizational governance and policy bodies to unleash technology based green value in CPEC.

Limitations and Future Research

The experiment has a cross-sectional design and, as opposed to some other studies, leaves limited scope to establish causal relationships in theory and practice. Moreover, the sample group inhabits the CPEC linked firms, which restricts the external validity of the results to those organizations that remain outside of this constellation. Future research is to be conducted in a longitudinal or cross-country comparative style and take place to study how time dynamics and environmental differences influence green capability accession, blockchain incorporation, and the ever-changing role of the digitalized infrastructure in sustaining performance.

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