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Carbon Management Systems and Environmental Performance: The Role of Technological Capability as a Mediator

(*Sistem Pengurusan Karbon dan Prestasi Alam Sekitar: Peranan Keupayaan Teknologi Sebagai Perantara*)

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ABSTRACT

Manufacturing firms are increasingly pressured to mitigate carbon emissions resulting from their operations, mainly due to stakeholders' negative reactions to environmental pollution. However, inadequate carbon management and technological capability can impede firms' environmental performance, producing a competitive disadvantage. Therefore, this study adopts the Natural Resource-Based View to investigate the effect of carbon management systems on the environmental performance of Malaysian manufacturing firms, specifically via the mediating role of technological capability. To meet the research objectives, a survey was conducted among 115 manufacturing firms registered under the Federation of Malaysian Manufacturers. Data analysis using structural equation modelling revealed significant positive relationships between carbon management systems, technological capability, and environmental performance, with technological capability mediating the effect of carbon management systems on environmental performance. Industry players and policymakers can leverage these insights to enhance manufacturing firms' carbon management strategies and subsequently, attain the environmental performance levels necessary to achieve net zero emissions.

Keywords: Environmental performance; carbon management systems; NRBV, technological capability; manufacturing

ABSTRAK

Firma pembuatan semakin tertekan untuk mengurangkan pelepasan karbon yang terhasil daripada operasi mereka, terutamanya berikut reaksi negatif pihak berkepentingan terhadap pencemaran alam sekitar. Walaubagaimanapun, kekurangan pengurusan karbon dan keupayaan teknologi boleh menghalang prestasi alam sekitar firma, lalu menimbulkan kelemahan kompetitif. Oleh itu, kajian ini menggunapakai Natural Resource-Based View untuk menyiasat kesan sistem pengurusan karbon terhadap prestasi alam sekitar firma pembuatan Malaysia, khususnya melalui peranan pengantara keupayaan teknologi. Bagi memenuhi objektif penyelidikan, tinjauan telah dijalankan di kalangan 115 firma pembuatan yang berdaftar di bawah Persekutuan Pengilang Malaysia. Analisis data menggunakan pemodelan persamaan struktur mendedahkan hubungan positif yang signifikan antara sistem pengurusan karbon, keupayaan teknologi, dan prestasi alam sekitar, dengan keupayaan teknologi mengantara kesan sistem pengurusan karbon terhadap prestasi alam sekitar. Pemain industri dan penggubal dasar boleh memanfaatkan pandangan ini untuk memperbaiki strategi pengurusan karbon firma pembuatan dan seterusnya, mencapai tahap prestasi alam sekitar yang diperlukan untuk mencapai pelepasan sifar bersih.

Kata Kunci: Prestasi alam sekitar; sistem pengurusan karbon; NRBV; keupayaan teknologi; pembuatan

INTRODUCTION

The Malaysian manufacturing sector has emerged as a key driver of the nation's economic growth, contributing 23% to its Gross Domestic Product (GDP) in 2022 (World Bank 2023). However, the sector's rapid industrialisation has made it a major source of pollution, presenting significant environmental challenges in terms of air and water contamination, waste generation, and carbon dioxide emissions (Mokthsim & Salleh 2014; Sakundarini & Ghazala 2018; Christine et al. 2019). The situation in Malaysia is particularly alarming, with rising per capita carbon emissions that are largely attributed to industrial activities. Given their threats to both environmental and public health, firms engaging in environmentally irresponsible practices often face government fines, negative media attention, and loss of shareholder support, leading to significant declines in stock prices (Flammer 2013; Wong et al. 2018). Therefore, there is an urgent need to address the manufacturing sector's impact on the ecosystem through effective carbon management (World Bank 2023).

Among the strategies explored by scholars to enhance environmental performance (EP) within the manufacturing sector (Nuber et al. 2020; Jung et al. 2018; Bebbington & Larrinaga-González 2008), this study focuses on firms' carbon management systems (CMS) and technological capability (TC). Tang and Luo (2014) defined CMS as "a way to implement firms' carbon strategy or policy to enhance input-use efficiency, mitigate emissions and risks, and avoid compliance costs while gaining a competitive advantage." It encompasses the comprehensive management of carbon emissions across a firm's value chain (e.g., governance, operations, accounting, disclosure practices), thus playing a crucial role in minimising emissions and aligning with broader sustainability goals (CDP 2010; Zhu et al. 2022). High-quality CMS can be achieved through the integration of governance, internal processes, carbon dioxide monitoring, and communication efforts (Tang & Luo 2014).

TC, on the other hand, refers to a firm's resources, knowledge, and competencies in deploying advanced technologies to support environmental initiatives. It is widely recognised as an essential capability in gaining a competitive edge and supporting environmental management practices like CMS (Hart 1995; Wang & Chen 2018). In Malaysia, for instance, Petronas has implemented successful CMS by integrating energy-efficient technologies and carbon accounting practices, significantly reducing its carbon footprint. Similarly, Top Glove has harnessed its TC by adopting green manufacturing processes and investing in renewable energy, thereby minimising its environmental impact. These examples illustrate the potential of CMS and TC as powerful tools for advancing sustainable EP in the manufacturing sector.

Despite these advancements, a significant gap remains in effectively aligning CMS and TC to achieve superior environmental outcomes (Kitsis & Chen 2021; Wang et al. 2020; Baah et al. 2021). Many firms are reluctant to fully disclose their EP due to uncertainties in estimation, limited standardised reporting measures, and governance issues (Nishitani et al. 2020; Wang et al. 2019; Seman et al. 2019). The resulting lack of transparency hampers stakeholders' ability to assess and compare EP across firms, complicating efforts to improve sustainability (Borghei et al. 2016; Datt et al. 2019). These challenges are especially relevant for Malaysian manufacturing firms, where the effectiveness of CMS is not yet fully understood and the integration of TC is obstructed by reporting ambiguities, despite both being critical tools for improving EP. Therefore, this study aims to investigate the effect of CMS on EP in Malaysian manufacturing firms, specifically through the mediating role of TC. Grounded in the Natural Resource-Based View (NRBV), this research seeks to provide a comprehensive understanding of how firms can better utilise their environmental and technological resources to enhance and transform EP into a competitive advantage.

The novelty of this study lies in both its theoretical and practical contributions. Theoretically, it offers new insights into the efficient use of CMS and TC within the NRBV framework, filling knowledge gaps in the environmental management literature. Practically, the study undertakes a holistic assessment of EP by integrating key components of CMS (i.e., carbon governance, operations, accounting, and disclosure) to provide a more comprehensive understanding of firms' environmental practices (Woo & Kang 2020; Jager et al. 2020; Aguilera et al. 2021; Koebele 2019; Aldowaish et al. 2022). In doing so, it offers actionable insights to improve the sustainability of manufacturing operations.

The remainder of this paper is organised as follows. In the next section, a comprehensive review of the literature is presented, followed by the development of the hypotheses and the theoretical framework. The study's methodology is then described, after which the findings are reported and discussed. Finally, the paper concludes by addressing the study's implications and limitations.

LITERATURE REVIEW AND HYPOTHESES

CARBON MANAGEMENT SYSTEMS (CMS) AND ENVIRONMENTAL PERFORMANCE (EP)

The NRBV posits that pollution and emissions represent inefficient resource utilisation, leading to economic waste. To lower such waste and minimise operational costs, firms should implement pollution prevention measures (Hart & Dowell 2011). In this regard, studies have shown that factors like environmental strategy, green innovation, and environmental management accounting influence EP both directly and indirectly through mechanisms such as green entrepreneurship, proactive strategies, and environmental practices (Tan et al. 2022; Makhloufi et al. 2022; Zheng et al. 2020; Appannan et al. 2020; Anthony et al. 2019; Latan et al. 2018; Solovida & Latan 2017; Yu & Ramanathan 2016; Alt et al. 2015).

Building on the NRBV framework, Tang and Luo (2014) found that large Australian firms have achieved significant carbon reduction through robust CMS, particularly when firms proactively allocate resources and prioritise environmental measures. On a global scale, Luo and Tang (2016) highlighted that CMS quality is shaped by both internal and external factors, such as emission trading schemes and competitive pressures, across different firms and countries. Notably, Sial et al. (2022) stressed the critical role of carbon accounting within CMS in reducing carbon emissions, confirming that a well-implemented CMS facilitates EP. Drawing on these studies, it can be concluded that a proactive CMS, with elements such as carbon governance, operations, accounting, and disclosure, positively affects EP.

Despite its benefits, implementing CMS may also have drawbacks. Zhang and Chiu (2020) noted that the high costs and resource demands of these systems can pose challenges for smaller firms, leading to increased operational expenses and resource allocation issues, ultimately undermining EP. In addition, Siedschlag and Yan (2021), as well as Nguyen et al. (2021), identified technical inefficiencies in CMS that can cause inaccurate emission reporting and insufficient data for informed decision-making, which also harms EP. Ultimately, while CMS is a valuable resource, its effectiveness depends on how well it is implemented and integrated into a firm's operations.

Consistent with the NRBV, firms should prioritise long-term sustainability through environmental protection and pollution control, which garners stakeholder support and resources to enhance environmental outcomes (Li et al. 2016). Accordingly, this study proposes the following hypothesis:

H_1 CMS is positively related to EP.

CARBON MANAGEMENT SYSTEMS (CMS) AND TECHNOLOGICAL CAPABILITY (TC)

In effectively managing resources and capabilities to create strategic competitive advantages, firms must acknowledge the importance of environmental sustainability and social responsibility (Hart 1995; Hart & Dowell 2011). A firm's strong EP can enhance its competitiveness (Sari et al. 2022) by implementing activities and processes that conserve the environment (Dias et al. 2021). In this regard, TC refers to a firm's skills, knowledge, equipment, systems, and processes that offer it competitive advantages in executing technical tasks, creating new products, and managing operations efficiently (Al-Mamary et al. 2022). Ergo, this capability can improve firm performance (Ahmad et al. 2019) by helping firms strengthen their resources and stay ahead of their rivals (Rahmani & Keshavarz 2015).

Digital transformation is vital for maintaining competitiveness and requires TC for planning, implementing projects, and improving information systems (Kim et al. 2016; Teece & Linden 2017). Studies on TC emphasise its role in optimising capacity, quality, and technological diversity, which enhances organisational capabilities (Torres & Hasencleve 2016). With TC, adopting new technologies enables firms to transform their operations (Zhou & Wu 2010). However, Fernando et al. (2021) and Zailani et al. (2024) reported that firms face challenges when adopting new technologies (e.g., blockchain), including a lack of top management support and technological expertise. These barriers can similarly affect CMS adoption. Without robust leadership backing, it becomes difficult to allocate resources, prioritise initiatives, and drive necessary changes, thereby impeding the successful implementation of CMS along with its capacity to enhance TC.

In essence, CMS and TC are interconnected in their shared goal of enhancing a firm's competitive advantage. CMS addresses environmental and social responsibilities, while TC helps firms develop technical skills and capabilities; when integrated, they jointly support firms' sustainability, operational efficiency, and innovation. Overcoming challenges related to leadership support and technological competence is indeed crucial for the successful implementation of CMS and its integration with TC. Thus, the following hypothesis is postulated:

H_2 CMS is positively related to TC.

TECHNOLOGICAL CAPABILITY (TC) AND ENVIRONMENTAL PERFORMANCE (EP)

A firm's EP assesses how well it addresses environmental concerns while considering the economic and social impacts of its actions (Das 2017). As such, EP reflects firms' ability to manage environmental resources, reduce their carbon footprint, and operate sustainably, making it integral to eco-friendly efforts. This is especially pertinent in the manufacturing supply chain, where EP can yield economic benefits (Raut et al. 2017). Achieving positive environmental outcomes is thus crucial for maintaining a competitive edge and generating economic value, particularly for environmentally proactive manufacturing firms (Ong et al. 2019).

TC plays a vital role in enhancing green innovation and EP (Ong et al. 2019). Prior research has extensively explored the impact of TC on various facets of organisational performance, including innovation, competitiveness, customer satisfaction, strategic decision-making, system efficiency, and operational effectiveness (Parnell & Brady 2019; Szalavetz 2018; Limo 2016; Guerra & Camargo 2016; Rahmani & Keshavarz 2015; Tzokas et al. 2015). Feng et al. (2020) emphasised that in high-tech sectors, TC is instrumental in building long-term competitive advantages and enhancing a firm's industry standing, underscoring TC's critical role in driving organisational success.

However, the relationship between TC and EP is not always straightforward. AlNuaimi et al. (2021) found that innovation might prioritise short-term economic gains over environmental sustainability, potentially leading to increased resource consumption or waste. Similarly, Alojail and Khan (2023) observed that technological advancements often do not immediately benefit the environment, depending on how well they are integrated. Hassan and Ibrahim (2022) noted that improvements in operational efficiency might not enhance EP if environmental considerations are secondary. Moosa and He (2022) found that innovations driven by economic objectives may overlook environmental benefits, while Wagner (2007) suggested that the early stages of technological upgrades could initially increase resource consumption and waste before leading to long-term environmental gains.

Together, these studies highlight the significant and multifaceted role TC plays across industries, establishing it as a key determinant of firm performance. Extrapolating these insights to the Malaysian manufacturing sector, this study hypothesises that:

H_3 TC is positively related to EP.

THE MEDIATING ROLE OF TECHNOLOGICAL CAPABILITY (TC)

This study posits that TC serves as a mediator between CMS and EP, linking carbon management resources to improved environmental outcomes. Although prior research highlights TC's role in various performance indicators (Ahmad et al. 2019), its mediating effects remain ambiguous. For instance, although Wu et al. (2020) demonstrated TC's mediating role between corporate EP and financial performance, Filho and Moori (2018) found that TC only partially mediates the relationship between supply chain management and competitive advantage. Other studies argue that although TC is important, organisational factors like management commitment, culture, and strategic alignment significantly influence the CMS-EP relationship (Moosa & He 2022; Salleh & Sapengin 2023). Similarly, Bhatia (2021) emphasised that TC's role depends heavily on other factors such as organisational learning and proactive environmental strategies.

Ong et al. (2023) also highlighted the risk of focusing solely on TC, cautioning that doing so may overlook other critical factors (e.g., regulatory support and compliance incentives) which can enhance the impact of CMS on environmental outcomes. This indicates that TC may not always have a full mediating effect, and its influence can vary depending on the context. These findings suggest that TC alone may not be sufficient, and that integrating environmental objectives into business strategies is equally important. Notably, the literature suggests that TC may not always have a full mediating effect, implying that its influence might vary depending on the context.

Grounded in the NRBV, this study proposes that while a well-established CMS can improve EP, the effect is likely elucidated by the support of TC. Therefore, the following hypothesis is formulated:

H_4 TC mediates the relationship between CMS and EP.

THEORETICAL FRAMEWORK

Figure 1 presents the proposed conceptual model illustrating the relationships between CMS, TC, and EP. Based on the NRBV, this framework reflects both direct relationships (H_1, H_2, and H_3) and the indirect relationship (H_4) in the path model.

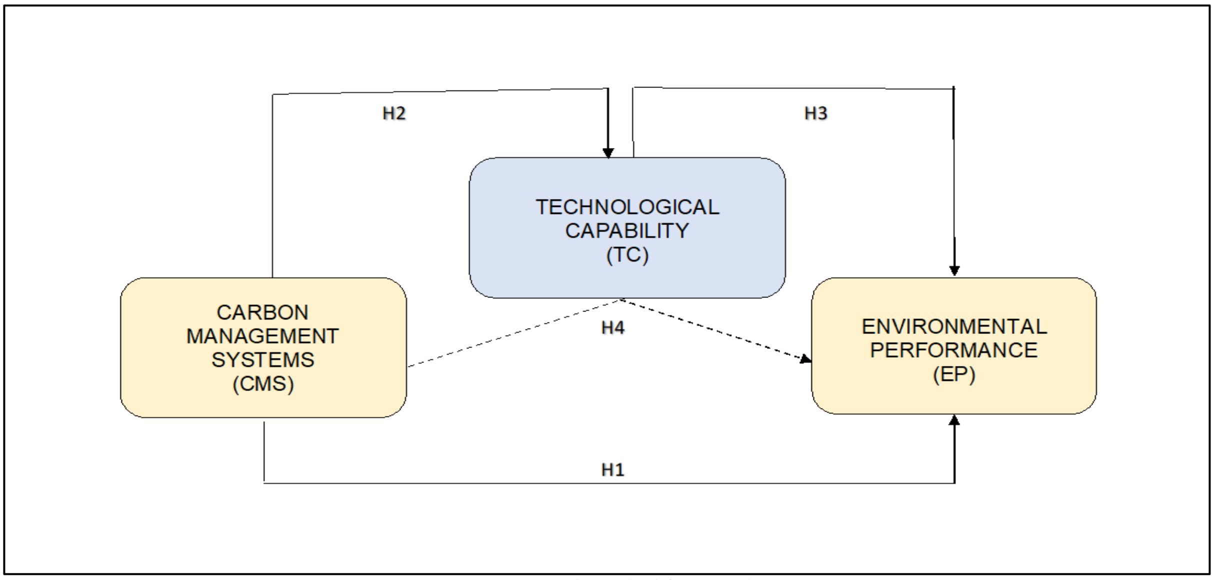

FIGURE 1. Theoretical framework
Source: Authors

METHODOLOGY

SAMPLING AND DATA COLLECTION

This study employed a quantitative approach, using survey questionnaires as the primary research instrument. Data was collected from manufacturing firms in Malaysia that are registered in the 52nd Edition of the Federation of Malaysian Manufacturers Directory. The target sample comprised various sub-sectors of the industry, with respondents specifically selected at the executive and managerial levels due to their close involvement in the firm's daily operations. The demographic details of both the firms and respondents are presented in Table 1. A total of 550 questionnaires were distributed, of which 115 were completed and deemed usable for analysis, yielding a response rate of 21%. This relatively low response rate aligns with findings from previous research in the manufacturing sector (Delgado-Verde et al. 2014; Agostini et al. 2017). The diversity within the manufacturing sector, including varying levels of technological adoption and process complexity across sub-sectors, can affect firms' willingness and ability to participate in research, particularly when the perceived relevance of the study to their specific operations is low.

TABLE 1. Demographic profile

Characteristics		Frequency	Percentage (%)
Ownership	Malaysia Owned	93	81
	Foreign Owned	22	19
Industry	Food, Beverage, and Tobacco	39	34
	Chemicals (including Petroleum)	10	8.7
	Fabricated Metals	17	14.8
	Basic Metal	4	3.5
	Machinery & Equipment	3	2.6
	Electrical & Electronics	10	8.7
	Plastics	6	5.2
	Non-Metallic Mineral	6	5.2
	Paper, Printing & Publishing	5	4.3
	Office, Accounting & Computing	2	1.7
	Other manufacturing	13	11.3
Firm’s age (years)	Less than 5	6	5.2
	Between 5 to 10	42	36.5
	Above 10	67	58.3
Number of Employees (full time)	Less than 100	40	34.8
	Between 100 to 200	39	33.9
	Above 200	36	31.3
Job Title	General Manager	18	15.7
	Plant Manager	4	3.5
	Senior Manager	63	54.8
	Department Manager	15	13
	Senior Executive	15	13
Experience (years)	Less than 5 years	10	8.7
	Between 5 to 10 years	42	36.5
	Above 10 years	63	54.8

MEASUREMENTS

This study’s survey instrument was designed to measure three key constructs: CMS as the independent variable, TC as the mediating variable, and EP as the dependent variable. The scale for CMS was adapted from Tang and Luo (2014), measured using standardised z-score values. The CMS items were grouped into four dimensions:

1. Carbon governance, which includes board function (board oversight of carbon management), risk and opportunity (management of carbon-related risks and opportunities), and staff involvement (staff engagement in carbon activities).
2. Carbon operation, which covers emission targets (emission reduction goals), policy implementation (execution of carbon policies), and supply chain emission control (emissions within the supply chain).
3. Carbon accounting, which consists of greenhouse gas accounting (emission measurement methods) and greenhouse gas assurance (data accuracy).
4. Carbon disclosure, which encompasses engagement with stakeholders (stakeholder involvement) and disclosure and communication (transparency of carbon-related information).

The measurement for TC was adapted from the Chantanaphant et al. (2013), and included questions measuring a firm's technology acquisition, technology operation, and technology upgrading capabilities. Finally, items for EP were adapted from Seman et al. (2019) and assessed a firm's compliance with environmental regulations, improvements in resource efficiency, reductions in environmental costs, and enhanced relationships with customers and suppliers. Both TC and EP were evaluated using a five-point Likert scale ranging from 1 (Lowest in Industry) to 5 (Highest in Industry).

RESULTS

DESCRIPTIVE ANALYSIS

The results of descriptive analysis are shown in Table 2. EP scores were slightly above 3.0; this suggests firms are performing well in environmental terms, reflecting a growing emphasis on sustainability that could enhance competitiveness and regulatory compliance. The CMS dimensions were standardised, yielding a mean of 0.000 and standard deviations close to 1.0. The variability in carbon governance, in particular, indicates inconsistent carbon management practices across firms, pointing to the need for stricter regulations. TC measures, which averaged around 3.0 as well, displayed variability in the technology operating capability (TC2), indicating that while firms are making consistent upgrades, they face challenges in effectively operating new technologies. This underscores the importance of investing in operational capabilities.

TABLE 2. Descriptive statistics

Variables	Measures	Mean	S. D
Environmental Performance (EP)	Compliance to environmental regulations (EP1)	3.405	0.643
	Improved efficiency in resources (EP2)	3.411	0.698
	Reduced environmental cost (EP3)	3.396	0.621
	Improved relationships with customers and suppliers (EP4)	3.409	0.688
Carbon Management Systems (CMS)	Carbon Governance (CG)	0.000	0.895
	Carbon Operation (CO)	0.000	0.609
	Carbon Accounting (CA)	0.000	0.630
	Carbon Disclosure (CD)	0.000	0.676
	Technology acquiring capability (TC1)	2.912	0.902
Technological Capability (TC)	Technology operating capability (TC2)	2.865	0.934
	Technology upgrading capability (TC3)	3.086	0.734

MEASUREMENT MODEL ANALYSIS

To test the hypotheses, data was analysed using structural equation modelling (SEM) via AMOS 29.0 software. Initially, a second-order confirmatory factor analysis was conducted to evaluate the measurement model's fit, followed by the estimation of the structural model using bootstrapping.

Second-Order Measurement Model Figure 2 illustrates that CMS was conceptualised as a second-order construct measured through its first-order components: carbon governance (CG), carbon operation (CO), carbon accounting (CA), and carbon disclosure (CD). TC was measured through three first-order constructs: technology acquiring capability (TC1), technology operating capability (TC2), and technology upgrading capability (TC3). EP was measured using four items: compliance with environmental regulations (EP1), improved efficiency in resource use (EP2), reduced environmental costs (EP3), and improved relationships with customers and suppliers (EP4).

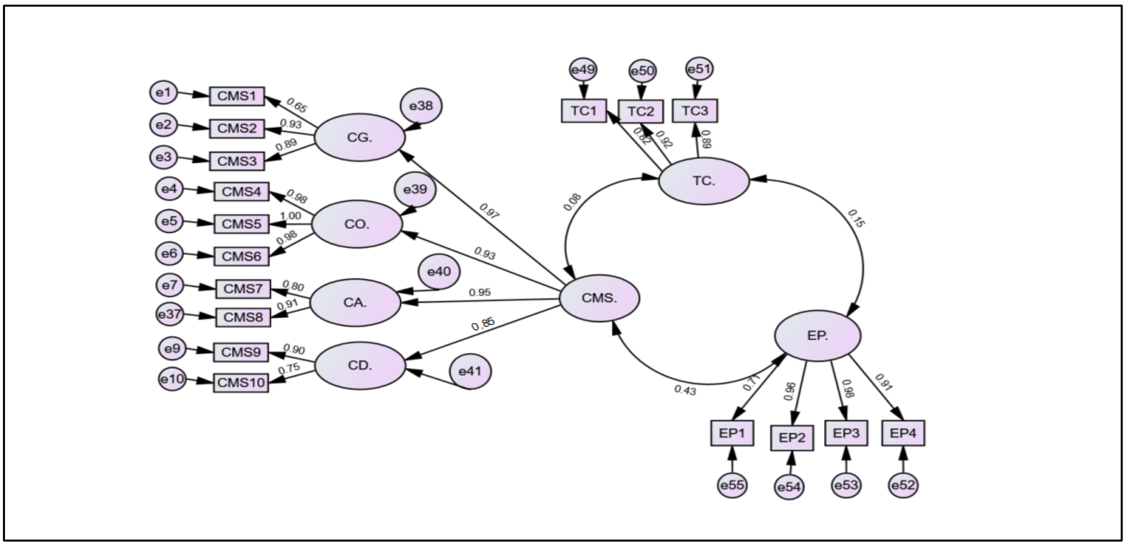

FIGURE 2. Second-order measurement model

Model Fit As shown in Table 3, the measurement model demonstrated acceptable fitness indices: χ^2/df = 1.998 (with a significant p-value of 0.001), SRMR = 0.0407, RMSEA = 0.068, GFI = 0.941, AGFI = 0.880, TLI = 0.941, and CFI = 0.943. These indices indicate that the model fit the data well, providing strong evidence to support the validity of the individual measures (Hair et al. 2010).

TABLE 3. Model fit (second-order)

Goodness of Fit Measures	$\chi 2$ /df	SRMR	RMSEA	GFI	AGFI	CFI	TLI
Recommended Value	2 to 5	< 0.08	≤ 0.08	≥ 0.90	≥ 0.90	≥ 0.90	≥ 0.90
Measurement Model	2.101	0.0407	0.068	0.941	0.880	0.941	0.943

Note: N=115; *p-value=0.001*; SRMR= standardised root mean squared residual; RMSEA= root mean square error of approximation; GFI=Goodness-of-fit Index; AGFI=Adjusted Goodness-of-fit Index, CFI=Comparative Fit Index; TLI= Tucker-Lewis Index (Kline 2005; Hu & Bentler, 1999)

Reliability and Convergent Validity All factor loadings exceeded the 0.50 cut-off criterion recommended for SEM (Hair et al. 2010). Composite reliability values were above the 0.70 threshold, confirming high internal consistency. Moreover, the average variance extracted (AVE) values exceeded 0.50 (Fornell & Larcker 1981), verifying the model's adequate convergent validity. These findings are summarised in Table 4.

TABLE 4. Reliability and convergent validity

Constructs	Dimensions	Items	Factor Loadings	CR	AVE
Carbon Management Systems (CMS)	Carbon Governance	CG	0.967	0.956	0.844
	Carbon Operation	CO	0.932		
	Carbon Accounting	CA	0.954		
	Carbon Disclosure	CD	0.815		
Technological Capability (TC)	Technology acquiring capability	TC1	0.819		
	Technology operating capability	TC2	0.824	0.776	0.717
	Technology upgrading capability	TC3	0.895		
Environmental Performance (EP)	Compliance to environmental regulations	EP1	0.711	0.941	0.801
	Improved efficiency in resources	EP2	0.963		
	Reduced environmental cost	EP3	0.975		
	Improved relationships with customers and suppliers	EP4	0.908		

Discriminant Validity As shown in Table 5, the square root of the AVE for each construct (bold numbers) exceeded the correlation values (non-bold numbers), meeting the discriminant validity criterion (Fornell & Larcker 1981). Additionally, Table 6 indicates that none of the HTMT values (45%, 66%, and 83%) surpassed the 0.85 threshold, further confirming the model's discriminant validity.

TABLE 5. Discriminant validity (Fornell & Larcker criterion 1981)

	EP	CMS	TC
EP	0.845		
CMS	0.431**	0.880	
TC	0.146**	0.079**	0.839

**Correlation is significant at the 0.01 level (2-tailed)

TABLE 6. Discriminant validity (HTMT ratio)

	TC	CMS	EP
TC			
CMS	0.451		
EP	0.667	0.828	

STRUCTURAL MODEL ANALYSIS

Upon confirming the reliability and validity of the second-order measurement model, the structural model was constructed to test the hypotheses (see Figure 3). All fit statistics were within acceptable ranges (Ullman 2001), as follows: CMIN/df = 2.597, GFI = 0.945, AGFI = 0.901, CFI = 0.959, TLI = 0.978, SRMR = 0.0467, and RMSEA = 0.071.

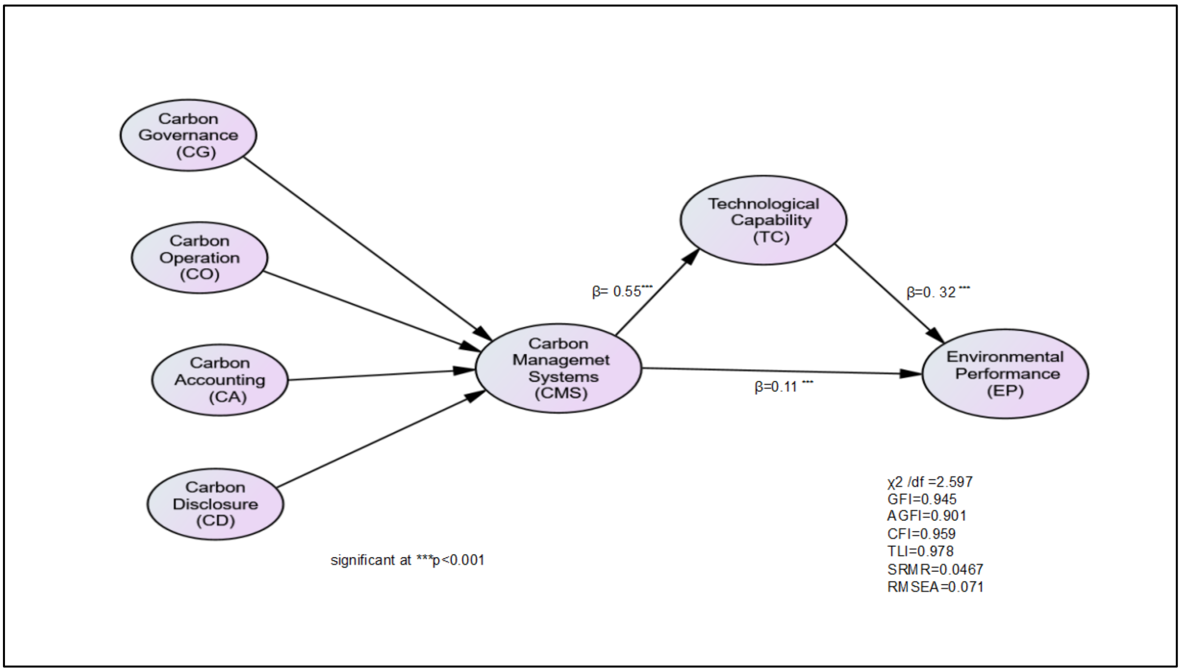

FIGURE 3. Structural model

Referring to Figure 3, the path coefficients (β) show the direction and relationship between the exogenous (independent) and endogenous (dependent) constructs. Table 7 presents the standardised direct and indirect effects' β values, along with standard errors, t-values, and p-values. The significance of the indirect effect was assessed using the bias-corrected two-tailed percentile method with 95% confidence intervals, derived through a bootstrapping procedure with 5,000 iterations.

TABLE 7. Hypothesis testing results

Hypothesis: Path	β	S.E.	t-value	p-value	LB 5%	UB 95%	Decision
H_1:CMS=> EP	0.111	0.014	7.928	0.000***	0.303	0.627	Supported

H_2: CMS => TC	0.551	0.083	6.638	0.000***	0.246	0.606	Supported
H_3:TC=> EP	0.323	0.089	3.620	0.000***	0.073	0.155	Supported
H_4:CMS=>TC=>EP	0.178	0.015	1.200	0.000***	0.047	0.443	Supported

Significance level at ***p<0.001

The results in Table 7 show a positive and significant direct relationship between CMS and EP (β=0.111, t=7.828, p<0.001), supporting H_1. Additionally, CMS was found to be significantly and positively associated with TC (β=0.551, t=6.638, p<0.001), providing support for H_2. The direct relationship between TC and EP (β=0.323, t=3.620, p<0.001), proposed in H_3, was also significant. For H_4, the results indicate a significant indirect effect of CMS on EP via TC (β=0.050, t=1.445, p<0.001, LB=0.074, UB=0.434), confirming the mediating role of TC. Further mediation analysis, as reported in Table 8, indicates that the computed Variance Accounted For (VAF) value is 0.62. That is, approximately 62% of the total effect from CMS to EP is accounted for by the indirect effect of TC. According to Hair et al. (2011), a VAF value between 20% and 80% suggests partial mediation. This study thus concluded that TC partially mediates the relationship between CMS and EP.

TABLE 8. Mediation analysis results

Path (mediated by TC)	Direct Effect(β)	Indirect Effects (β)	Total Effects	VAF	Mediation
CMS=>EP	0.111	0.178	0.289	0.62	Partial Mediation

DISCUSSION

This study has investigated the relationship between CMS and EP via TC as a critical mediator. CMS encompasses a comprehensive approach, including the governance, operation, accounting, and disclosure of carbon management, all aimed at improving EP. This strategy is closely tied to a firm's TC, specifically its ability to acquire, operate, and upgrade technologies. Consequently, TC is positioned as a key enabler that transmits the effectiveness of CMS. The synergy between CMS and TC is indeed vital for achieving superior EP and maintaining competitiveness in today's dynamic business environment.

The positive relationship found between CMS and EP highlights the importance of effective governance, efficient operations, accurate accounting, and transparent disclosure in carbon management. These elements can significantly contribute to a firm's compliance with regulations, improved resource efficiency, reduced costs, and stronger relationships with customers and suppliers, all of which cultivate competitive advantages. This study's findings align with previous research by Tang and Luo (2014), Luo and Tang (2016), and Sial et al. (2022), which emphasise that firms prioritising robust CMS practices experience enhanced compliance, cost efficiency, and stakeholder engagement.

However, it is noteworthy that carbon governance's effectiveness in integrating environmental goals into broader strategic objectives can be constrained by varying regional standards and the need for continuous regulatory updates. Concurrently, while carbon operation initiatives can enhance operational efficiency and reduce the environmental footprint, balancing these efforts with other business goals is crucial to avoid potential trade-offs. Likewise, despite carbon accounting's critical role in strengthening compliance and stakeholder trust, its effectiveness may be limited by the complexity of diverse accounting standards and emission tracking difficulties, especially for multinational firms. Lastly, firms must be mindful that carbon disclosure improves transparency and reputation but can also increase external scrutiny from stakeholders, placing additional pressure on firms to continuously improve.

Next, the positive effect of CMS on TC is supported by studies such as Rahmani and Keshavarz (2015) and Wang and Chen (2018), which indicate that CMS alone is insufficient for achieving significant environmental improvements. Rather, robust TC, entailing technology acquisition, process optimisation, and ongoing technology upgrades, is essential to fully leverage the benefits of CMS. Nevertheless, investments in acquiring new technologies and continuously upgrading existing ones, albeit vital for EP and competitive advantages, require careful planning due to high costs, potential resistance to change, and other challenges that require strategic management. Firms must also balance other business goals with the optimisation of operational processes through advanced technologies, even though the latter directly enhances resource efficiency and EP.

This study also established a positive relationship between TC and EP, suggesting that firms with robust TC practices—such as collaborating with research institutions, cultivating a skilled workforce, and adopting adaptive production processes—are better positioned to improve EP. Studies by Parnell and Brady (2019), Ong et al. (2019), and Raut et al. (2017) corroborate this finding, showing that engagement with scientific research, skilled technical staff, and frequent process modifications contribute to the development and implementation of environmentally friendly technologies. TC's impact on EP is multifaceted, influencing regulatory compliance, resource efficiency, cost reduction, and stakeholder relationships. Exceeding the minimum requirements of compliance using technology can provide a competitive edge to firms. Similarly, effective TC enhances resource efficiency and reduces operational costs, which supports profitability. However, initial technology investments are often substantial, and managing the trade-off between TC's benefits and other business goals can be complex. Furthermore, in building strong stakeholder relationships to achieve environmental goals, firms may find it difficult to align diverse stakeholder interests.

Notably, this study underscores the crucial mediating role of TC in the CMS-EP relationship. TC not only manifests the implementation of CMS but also amplifies its positive impact on EP. This finding aligns with the perspectives of Filho and Moori (2017), Wu et al. (2020), and Bhatia (2021), who argued that TC serves as a critical organisational resource that strengthens internal processes and drives environmental improvements. It is also consistent with Fernando et al. (2023), who emphasised that TC not only directly enhances EP but also integrates effectively with broader strategic initiatives like CMS. Specifically, TC acts as a bridge, facilitating the effective utilisation of CMS and transforming carbon management efforts into tangible environmental benefits. However, focusing solely on TC as a mediator may be limiting. Other factors, such as innovation capacity, organisational learning, and external stakeholder engagement, could also play significant roles in the CMS-EP relationship. Future research could explore these alternative mediators to provide a more comprehensive understanding of the mechanisms through which CMS influences EP. Investigating moderators, as well, could yield insights into the conditions in which CMS and TC better interact to drive EP.

CONCLUSION AND IMPLICATIONS

This study's findings indicate that both CMS and TC have a significant and positive impact on EP in the Malaysian manufacturing sector. Furthermore, TC partially mediates the relationship between CMS and EP, underscoring its role as a critical enabler in achieving improved environmental outcomes. Theoretically, this research broadens the application of the NRBV by demonstrating the importance of aligning environmental strategies with organisational operations and embedding environmental considerations into core functions. Indeed, a holistic approach to carbon management, where CMS is integrated into every managerial and operational aspect of an organisation, can significantly enhance EP. Additionally, considering the crucial role of TC as a mediator, this study adds value to the literature by proving that firms can effectively leverage the positive effects of CMS on EP by investing in TC. The findings demonstrate how technological advancements can be leveraged to maximise the environmental and operational benefits of resource-based strategies, further expanding the NRBV's relevance.

The practical implications of the findings are significant for both policymakers and industry players. For policymakers, the study underscores the need to promote sustainable practices by internalising the environmental costs of carbon emissions. Policymakers can enhance carbon pricing mechanisms, such as Voluntary Carbon Markets, Emissions Trading Systems, carbon taxes, and carbon credits, which are essential for incentivising businesses to reduce their carbon footprints and align economic activities with sustainability goals. For manufacturing industry players, the findings highlight opportunities for cost savings and revenue generation by accounting for the carbon costs of production. Mechanisms like the Carbon Border Adjustment Mechanism can help firms avoid regulatory penalties while creating opportunities to capitalise on carbon efficiency. By integrating these carbon control mechanisms into their operations, firms can enhance their competitiveness and contribute to global carbon reduction efforts.

LIMITATIONS AND FUTURE RESEARCH

Notwithstanding its contributions, this study has certain limitations. First, it focuses solely on environmental sustainability, neglecting firms' economic and social performance. Future research should adopt a triple-bottom-line approach, incorporating the "people, planet, and profit" framework to offer a broader sustainability perspective. Additionally, the reliance on surveys from top officials may introduce bias. Future studies should combine objective survey data with qualitative data, such as from interviews or focus groups, to capture a wider range of insights. This mixed-method approach would provide a deeper understanding of how CMS enhances environmental outcomes. Finally, the contact information utilised in this study to access manufacturing firms may be outdated; as such, the sample may not fully represent smaller industry players and sub-sectors. Future research could adopt a more nuanced focus that narrows to specific sectors (e.g., food and beverages, chemicals, electronics), so as to better address the unique environmental challenges and sustainability practices of these industries.

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