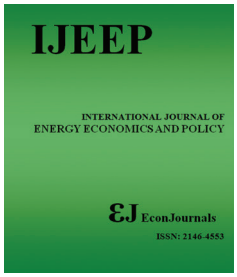

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Digital and Green Synergies: How Malaysia is Cutting Carbon Emissions through Supply Chain Innovation, Renewable Energy and Upcycling?

Amena Sibghatullah[1]*, Mariam Sohail[2], Firdaus Abdullah[3], Masturah Ma'in[1], Mohinur Rakhimova[4]

[1]Universiti Teknologi MARA, 42300, Selangor, Malaysia, [2]De Montfort University Kazakhstan, 050022, Almaty, Kazakhstan, [3]Universiti Teknologi MARA, Sarawak, Malaysia, [4]Department of Macroeconomic policy and forecasting, Tashkent State University of Economics, Uzbekistan. *Email: amena@uitm.edu.my

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ABSTRACT

This paper aims to analyze the influence of the digital economy, green supply chain management, renewable energy consumption, and upcycling on carbon emissions in Malaysia. These are crucial objectives as the country strives to achieve economic development without compromising the environment, given that the two are in an unending conflict in society. Thus, the study's objective is to examine the role of digitalization, renewable energy use, green supply chain management and upcycling in carbon emissions in Malaysia. It aims to establish whether these factors are statistically significant and offer policy implications for projecting their efficiency gains. Therefore, a quantitative method, using the employed pooled ordinary least squares (POLS) regression analysis, was used to test the correlation between key variables of sustainability and carbon emissions for the period of 2014-2024. The Durbin-Watson test and the VIF analysis were also carried out to test the model that was used to diagnose the independent variables. The outcome reveals that increasing the digital economy's scale and renewable energy consumption reduces carbon emissions. As for the green supply chain management and upcycling practices, there is no significant correlation between them, which can be attributed to the fact that the implementation of such practices has not reached maturity. Some barriers include lack of infrastructure, policies and inadequate funding that may seasonally limit their maximum capacity. The study implies that digitalization and renewable energy, which mitigate carbon emission practices, work well. In contrast, green supply chain management and upcycling need more policy encouragement and well-developed infrastructure. For Malaysia to achieve its long-term reduction targets, it is necessary to have better policies that cover sustainability laws in industries, provide incentives for green technology and invest in upcycling industries.

Keywords: Digital Economy, Green Supply Chain, Renewable Energy, Upcycling, Carbon Emissions, Malaysia
JEL Classifications: Q55, Q56, O33

1. INTRODUCTION

Malaysia, like other developing countries, is struggling to balance the divide between, on the one hand, the quest for continuous economic growth and the protection of the environment. This has inevitably caused the nation to embrace other approaches to cutting its emissions, like technology and sustainability (Chua et al., 2023). Hence, this paper aims to examine the effects of the digital economy, green supply chain management, renewable energy take-up, and upcycling or reusing on the carbon emissions of Malaysia.

Malaysia has always been inclined to focus on energy export-dependent industries, which enhanced Malaysian economic development through GDP and employment. However, this growth has several effects, including the emission of greenhouse gases into the atmosphere, which requires adopting a more sustainable Green technology (Ludin et al., 2025). The main lesson lies in the

fact that it is possible to achieve economic development without causing harm to the environment – a matter of concern that is typical for developing countries.

The digital economy is currently an essential aspect of Malaysia's economy, contributing about 22.6% to the GDP (Edrak et al., 2022). What measures can be taken to increase production efficiency? One is the active use of digitalization in technologies and energy consumption analysis. For instance, sectors such as data centers are essential for business operations, yet they consume energy. New investments in data centers, especially in Johor, have been making headlines, and people have been worried about power consumption (Halim-Lim et al., 2025). These effects have resulted in organizations looking for renewable energy and efficient technologies.

Green supply chain management (GSCM) is a factor of sustainability that considers environmental aspects in the supply chain to reduce the environmental impact. Today, companies worldwide and in Malaysia are adopting green goals like zero carbon emissions and establishing sustainable ecosystems in the supply chain (Azmi et al., 2024; Sohail et al., 2024; Suleman et al., 2024). Nonetheless, there are barriers in GSCM, such as infrastructure and the embracing and establishing of sound policies on sustainability (Arias et al., 2024).

To meet the condition, the Malaysian government has planned to increase the proportion of the power capacity from renewable energy to 31 percent by 2025, and the effort towards reducing carbon emission by 45% by the year 2030 has been set. According to the energy statistics for 2022, the installed renewable energy capacity was over 9,000 MW, showing that the current capacity was 50% higher than that of 2013. Measures like the centralized solar power plant and the integrated hydro-floating mode are part of diversifying the energy resources rather than depending upon fossil energy (Labaran and Masood, 2023; Nosheen et al., 2024). The former is of equal importance as it addresses challenges related to climate change and sustainable development.

Upcycling, reusing waste products to create goods of new value, is a key aspect of a circular economy since it helps to decrease wasting resources. Although Malaysia has recently adopted waste-to-energy projects and raised concerns about increasing the recycling rate, upcycling is still nascent. Sustainable and Circular Economy Roadmap for the future going up to 2023-2040 focuses on better resource utilization and minimizing waste (Leong et al., 2022). Consequently, there is a scarcity of research to establish the effect that upcycling has on carbon emissions on a national level in Malaysia, and additional work needs to be done on it.

For Malaysia to efficiently serve the global market needs while effectively using resources, integrating digital skills, green supply chain practices, renewable energy sources, and an upcycling system must be adopted. Nevertheless, certain challenges remain, namely structural needs, policy compliance and awareness. These challenges will be discussed to implement sustainable development and a low-carbon society through cooperation among the government, private sectors, and society.

2. LITERATURE REVIEW

2.1. Digital Economy and Carbon Emissions

The issues of the role of the digital economy, which may be defined as the extent to which digital technologies are incorporated into different industries, for carbon emissions are complex. On the one hand, digitalization supplemented by AI can improve the global energy efficiency rate and use of resources in general (Dong and Xiaoli, 2024) For instance, the integration of artificial intelligence (AI) and the use of Internet of Things (IoT) gadgets assist in enhancing the conservation of energy in the manufacturing and transportation industries, hence minimizing the emissions of greenhouse gases (GHGs) (Xia and Tang, 2024).

However, with the advancement of digital services, energy consumption is seen going a notch higher. Currently, data centers that are crucial for enabling many digital uses are very energy intensive. Data centers and transmission networks consume about 1% of global electricity, and the digital sector contributes between 2% and 4% of GHG emissions (Freitag et al., 2021). This energy demand is expected to increase with more adoption of digital technologies. The problems of digital technologies are not limited to energy use only. Technology products are common devices used in the modern world, and their manufacturing and destruction lead to the formation of electronic waste, which is a widespread environmental problem. The use of digital devices is increasing, meaning higher production and thus, more resources are being extracted, and energy is being used. Moreover, when these devices become obsolete, they create pollution since they release toxic substances (Kurniawan et al., 2022).

The digital economy is quite influential in Malaysia, contributing to about 22.6% of the GDP, as reported by the Malaysia Digital Economy Corporation (2022). The increasing usage of social infrastructure like data centers for hosting is now seen as problematic regarding energy consumption and, hence, carbon footprint. To counter these effects, there is increasing concern about embracing cleaner energy sources and improving efficiency in IT systems. For instance, organizations are venturing into deploying renewable energy sources in computer facilities to minimize the environmental impact of virtual processes (Newman et al., 2024).

2.2. Green Supply Chain Management

GSCM is an approach to implementing environmentally sound principles in supply chain operations from the design phase to the disposal phase. The overall outlook of GSCM as a concept aims to achieve two objectives: one is to eliminate the effects of environmental degradation by Supply Chain activities such as the buying process and transportation, among others (Lerman et al., 2022).

It has also been noted that the level of carbon emissions reduction resulting from implementation differs from one region to another and from one industry to another. As observed in some sectors, implementing green practices has reduced emissions of specified GHG. For example, to the extent that the companies have incorporated efficient distribution and green purchasing

mechanisms, there are minimal carbon emissions (Liu et al., 2024). However, there is always a varying degree of such reductions in the industry type, the legal requirements, and technological incorporation.

Now, in Malaysia itself, the following plans have been implemented in the effort towards the enhancement of GSCM: There has been the adoption by the government of policies that seek to promote sustainable production by industries so that sustainable development and the economy go hand in hand (Assumpção et al., 2022, Sohail et al., 2024). However, the major drawbacks include poor awareness, lack of skill set, and inadequate population funding to embrace this useful method. In order to overcome these barriers, concerted efforts by the government, industry players, academia, and academia should create capacity and incentives for green practices (Roh et al., 2022).

2.3. Renewable Energy Adoption

Using a renewable source of energy is another effective measure to curb emissions resulting from the use of fossil fuels. By tapping solar, wind and hydraulic energy, renewable energy is less dangerous to the environment than conventional energy sources (Khan et al., 2022). Malaysia has realized that renewable energy is key to attaining the set carbon emission targets. There are targets for the development of renewable energy that have been established at the government level to increase the share of renewable energy in total electricity consumption. Legal measures that have been put in place to promote investing in renewable energy consist of feed-in tariffs and tax exemptions (Abbas et al., 2023). These measures have gradually led to a little enhancement of renewable energy capacity to reduce carbon intensity (Twumasi et al., 2022).

Nonetheless, the mentioned achievements indicate that there are still obstacles to adopting renewable energy in the national grid. Some challenges include the stability of the electric grid and storage and the fact that some renewable energy sources are not constant. Meeting these challenges calls for constant advancement in technology, the development of infrastructure, and the provision of and enabling policies and legislation (Zeng et al., 2022).

2.4. Upcycling Practices

Upcycling is the process of taking useless material and using it to form a product of higher value than the original item; there will be less needed to extract the raw material used to produce the upcycled material. This practice helps reduce the common global problem of wastage while helping the practice of using what is referred to as a circular economy (Caldera et al., 2022). Several studies have been conducted on upcycling materials. However, few have explored the effects of upcycling on reducing national carbon emissions. Despite these, it is difficult to measure the extent of reduction on a national scale by upcycling and the disparity in the levels and practices of various industries (Sung, 2023).

Upcycling has not been fully embraced in Malaysia, but it is gradually becoming an environmentally friendly practice. Both businesspersons and institutions have risen to the challenge of repurposing garbage as precious items such as clothes and construction materials (Singh, 2022). For instance, organizations are looking for ways to harness agricultural waste to produce environmentally friendly products. However, for upcycling to achieve its full potential in the fight against the cuts in carbon emissions, there is a need for policy backing, awareness creation, and research and innovation funding (Bigolin et al., 2022).

2.5. Conceptual Framework

With the help of the selected research model, the cause-and-effect model, four independent variables are identified to affect the dependent variable of carbon emission reduction. To investigate indirect relationships, the study includes a mediator variable while it employs a moderating variable for the external factors. This will ensure that the impacts of digital transformation, sustainable supply chains, renewable energy, and up cycling in combating environmental degradation in Malaysia are comprehensively captured within this conceptual framework.

The DE is a vital factor that plays a positive role in sustainability as it helps firms cut their energy consumption and other resources, besides improving their productivity. Specifically, through AI, blockchain, and the smart grid, the use of digitalization greatly influences curbing carbon footprints (Fan et al., 2023). As data centers and e-business domains spread thick and fast within Malaysia, energy consumption becomes a significant matter of concern, with digital sustainability being an important part of the emission cutback plan (Le et al., 2022). Green Supply Chain Management (GSCM) looks at making supply chain management environmentally friendly. These are green purchases, green logistics that can be reverse logistics and green manufacturing (Vangeri et al., 2024). When entered into implementing GSCM, the firms may use less materials and energy and reduce GHG emissions. However, the advantage of this type of structure is disease-dependent on the level of issuance of such structures in different fields and the degree of compliance with sustainability standards (Karmaker et al., 2023).

Another reason is that the use of renewable energy (REA) also has a significant impact on releasing carbon into the environment. Fossil energy is still widely used in different industries today. Society needs to move towards the use of renewable resources like solar, wind and hydropower energy (Qin et al., 2022). Malaysia is dedicated to developing more renewable energy; the country target is to utilize country's target is to utilize 31% renewable energy by 2025. The efficiency of this process relies on the scalability, investment in incentives and, most importantly, the integration of renewable energy in the industrial and residential areas (Yuan et al., 2022).

The upcycling practices (UP) here refer to the recycling of waste material to produce superior products and useful goods without using the raw materials that would otherwise form the basis of their production (Balu et al., 2022). It should be noted that while recycling is a useful process used to reuse many materials, it generally involves downgrading material quality, while upcycling does not. This is because it helps in shifting from a linear product usage whereby there is the usage of material

and dumping of products after some time to a circular economy where the use of products is long-term, reducing carbon footprint (Gnatiuk et al., 2022).

The carbon emissions reduction (CER) is used as the dependent variable as it shows the extent of the success of sustainable strategies to reduce greenhouse gas emissions and, therefore, environmental degradation. Digitalization's efficiency, green supply chain management practices, renewable energies, and upcycling are evaluated based on their capacity to reduce Malaysia's carbon footprint and their contribution toward the international climate agreements, the Paris Agreement, in particular (Lo and Cong, 2022).

The circular economy practices focalized as CEPs are considered an intermediate variable connecting the independent variables to decrease carbon emissions. It refers to a business model of production and consumption that endeavors to keep the materials recycled and reused instead of ending up in a landfill. With the application of CEP, organizations and governments establish a closed-loop flow where materials are sustainably recycled over time, thus fully reducing carbon emissions in the long run (Yao et al., 2022).

Therefore, the impact of sustainability initiatives on organization and society is greatly influenced by the RP. These encourage or hinder policies that range from government incentives, carbon taxation, regulatory frameworks, and enforcing mechanisms of digitalization to green supply chains, renewable energy, and upcycling (Issa and In'airat, 2024). Viable policy enforcement guarantees that sustainability measures should not only be stated but also required to make proper practices universal, thus influencing the company and the citizens on low-carbon initiatives. On the other hand, nicely shown, they have the potential to slow down the advancement if the appropriate regulations are not put in place or are inadequate in their support of sustainability initiatives (Pan et al., 2022).

2.6. Research Model

Figure 1 presents an overview of the study's theoretical model, which defines the connections between sustainability factors and their effect on CER. Thus, the independent variables of DE, GSCM, REA, and UP have both a direct effect on CER and an indirect effect that occurs through CEP. It involves the digitalization of processes, managing the supply chain, using renewable energy, reusing waste, and recycling, among others. Moreover, Regulatory Policies (RP) is a control variable that influences the magnitude and significance of the coefficients of the IVs with both CEP and CER. The above diagram presents the direct paths from IVs to CER and the indirect paths through CEP to represent the mechanism through which policy support, technological innovation and sustainability initiatives influence carbon emission reduction in Malaysia.

2.7. Hypothesis

H_1: The Digital Economy (DEI) has a significant negative impact on Carbon Emissions Reduction (CER).

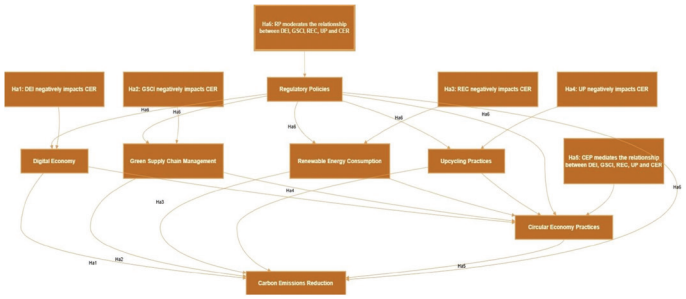
H_2: Green Supply Chain Management (GSCI) has a significant negative impact on Carbon Emissions Reduction (CER).

H_3: Renewable Energy Consumption (REC) has a significant negative impact on Carbon Emissions Reduction (CER).

H_4: Upcycling Practices (UP) have a significant negative impact on Carbon Emissions Reduction (CER).

H_5: Circular Economy Practices (CEP) mediate the relationship between sustainability initiatives (DEI, GSCI, REC, UP) and Carbon Emissions Reduction (CER).

H_6: Regulatory Policies (RP) moderate the relationship between sustainability initiatives (DEI, GSCI, REC, UP) and Carbon Emissions Reduction (CER).



3. METHODOLOGY

The study adopted sustainable development goals as the framework to reveal how to maintain economic growth in the long run while at the same time maintaining stability in carbon emission and resource use. The study's objective is to analyze the DEI, GSCI, REC and UR on the CO_2 emissions in Malaysia. The model also uses the systems approach as the method of investigation, which was developed based on prior empirical work done in the field of sustainable economic development and environmental policy.

3.1. Data Collection

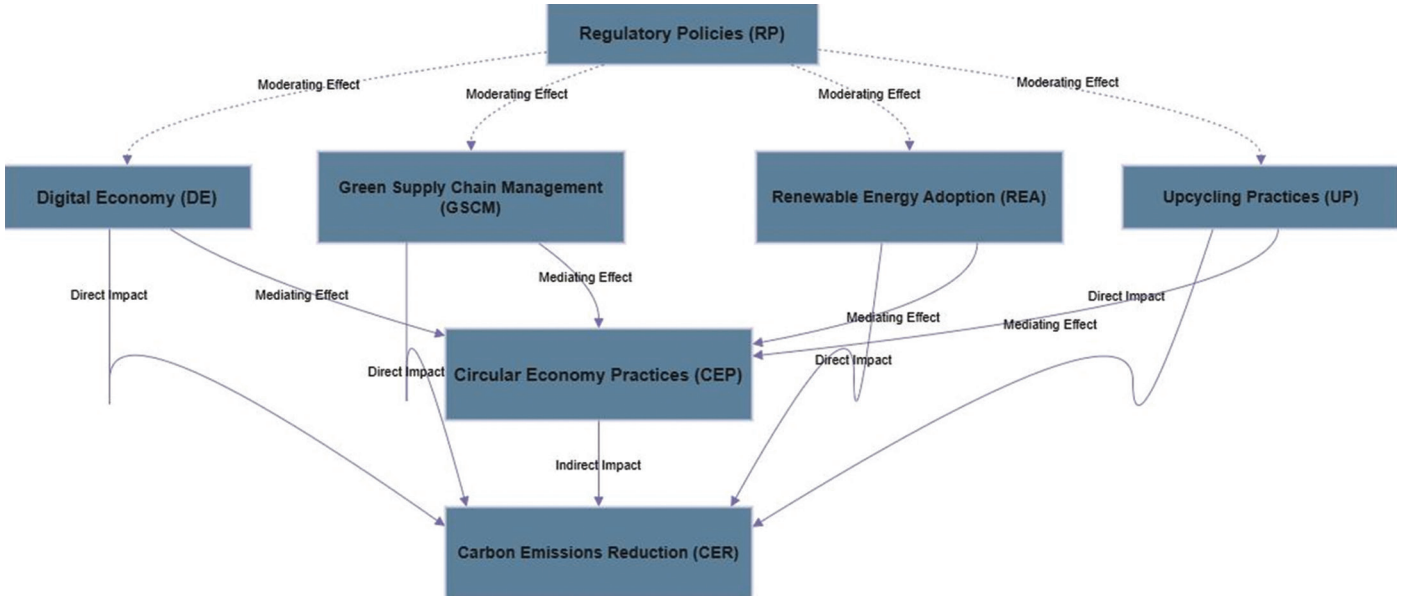
In this study, the data collected includes annual from 2014 to 2024 to relate the independent and the dependent variables. The data sources include:

- Malaysia's Department of Statistics (DOSM) – for macroeconomic indicators, digital economy growth, and carbon emissions data.
- International Energy Agency (IEA) – for energy consumption trends and renewable energy adoption statistics.
- Use World Bank Open Data to complement the dataset regarding economic and environmental conditions to maintain reliability and comparability across countries.

The factors used in this study are as follows:

- Carbon Emissions (CO_2) (Dependent Variable)—The measurement is in metric tonnes per capita, which shows Malaysia's greenhouse gas emissions in a year.
- Digital Economy Index (DEI) (Independent Variable): This is a proxy for Malaysia's digital economy, whereby the country's level of digitalization has been determined by the Internet, growth of e-commerce and investment in information and communication technology.
- Green Supply Chain Index (GSCI) (Independent Variable): This measures sustainable purchases, environmental transportation and disposal in Malaysia's industrial supply chain.

Figure 1: Research model



- Renewable Energy Consumption (REC) (Independent Variable) refers to the amount of renewable energy consumed in Malaysia as a percent of the overall energy consumed.
- Upcycling Rate (UR) Independent Variable—This variable is used to determine the extent to which products derived from waste materials are recycled to enhance the circular economy.

To analyze data reliability, all gathered sets of data are checked against data from various environmental reporting authorities and sustainable development organizations. Sometimes, the predictors are made to be logarithmic if their distributions are somehow skewed to make them homoscedastic.

3.2. Econometric Model

A multiple linear regression model is employed to assess the impact of independent variables on carbon emissions

$$\ln(CEit) = \beta 0 + \beta 1 \ln(DEIit) + \beta 2 \ln(GSCIit) + \beta 3 \ln(RECit) + \beta 4 \ln(URit) + \epsilon it$$

CEit represents the logarithm of Carbon Emissions (CO_2) for country at time.
DEIit denotes the Digital Economy Index, a proxy for digitalization growth.
GSCIit represents the Green Supply Chain Index, reflecting sustainable supply chain practices.
RECit is Renewable Energy Consumption, measuring the percentage of total energy derived from renewable sources.
URit is Upcycling Rate, measuring the extent of recycling and circular economy efforts.
$\beta 0$ is the constant term.
$\beta 0+\beta 1$ are the coefficients for independent variables.
ϵ_{it} is the error term.

Working on the logarithmic form of the variables makes it possible to estimate the model's elasticities; therefore, the coefficients represent percentage changes in the carbon emissions for an interval change of one percent of the independent variables.

The model suggests that there is less carbon emission when digitalization and green supply chains are increased, but the adoption of renewable energy and upcycling can have both positive and negative impacts based on the country's policies and conditions. The variables have been chosen in relation to sustainable energy policies and the environmental aspect.

3.3. Data and Estimation Technique

The data used in this research are annual data from 2014 to 2024 for Malaysia. The data sources include:

- Malaysia's Department of Statistics (DOSM): Provides macroeconomic indicators, digital economy growth, and carbon emissions data.
- International Energy Agency (IEA): Supplies energy consumption trends and renewable energy adoption data.
- World Bank Open Data: Complements the dataset with economic and environmental statistics for cross-country comparability.

The analysis method used in this research is the POLS regression by panel, which enables cross-sectional and temporal analysis. Several checks have been conducted to confirm that the model's stability is as follows:

- Durbin-Watson Test for autocorrelation in residuals.
- Dummies testing and multicollinearity checking using Variance Inflation Factor (VIF).
- Heteroskedasticity Tests will be used to test the assumption of homoscedasticity, which means that there are variations in the variance of the model's error terms.

To ensure more solidity in the model, methods like the Fixed Effects and Random Effects models are considered to check the discrepancies. A test for the stability of Coefficients will also be conducted to determine the robustness of the estimates by changing the model specification.

3.4. Variable Definitions and Measurements

Code	Variable	Measurement	Source	Expectations
DEI	Digital Economy Index	Digitalization growth proxy	Malaysia Digital Economy Corporation (MDEC)	Negative (-)
GSCI	Green Supply Chain Index	Sustainable supply chain practices index	Bureau Veritas	Negative (-)
REC	Renewable Energy Consumption	Percentage of total energy from renewable sources	International Energy Agency (IEA)	Negative (-)
UR	Upcycling Rate	Extent of recycling and circular economy efforts	Sustainable and Circular Economy Roadmap	Negative (-)
CER	Carbon Emissions Reduction	Metric tonnes per capita	Malaysia Department of Statistics (DOSM)	Not Applicable

The table outlines the three factors that were selected to be applied to the study. The first part of the table defines the measurements of the variables. In contrast, the second part defines the sources of data to be used for the analysis, and the last part of the table indicates the expected impact that the variable would make concerning carbon emission reduction in Malaysia. Malaysia Digital Economy Corporation MDEC uses the Digital Economy Index DEI that measures digitalization's growth; this variable is expected to be the inverse of carbon emission, implying that, as DEI rises, more digitization will lead to increased emission reductions through efficiency. GSCI, available from Bureau Veritas, assesses the extent of sustainability strategies in the supply chain and is expected to contribute toward reducing emissions through green production and transportation. Likewise, Renewable Energy Consumption (REC), obtained from the International Energy Agency (IEA) accounts for energy from renewable sources. It is intended to reduce emissions as much as fossil fuels. The Upcycling Rate (UR) extracted from the Sustainable and Circular Economy Roadmap represents a recycling and circular economy that may lower emissions in the future due to reduced waste and resource consumption. CER is the dependent variable obtained from Malaysia's Department of Statistics (DOSM), which shows the extent of its emission reduction effort. The negative signs of all the independent variables suggest that advancement in these areas will help reduce carbon emissions consistent with the sustainable growth of Malaysia.

3.5. Data and Estimation Technique

The data for analyzing the impact of the digital economy, green supply chain practices, renewable energy consumption and upcycling on carbon emissions in Malaysia was collected from the year 2014 to the year 2024. The identified variables are DEI, GSCI, REC, UR and CER. The sources of data involve the Malaysia Digital Economy Corporation (MDEC), Bureau Veritas, International Energy Agency (IEA), Malaysia Sustainable and Circular Economy Roadmap, and the Department of Statistics Malaysia (DOSM). Therefore, to test the link between the variables, the Pooled Ordinary Least Squares (POLS) were adopted. This enables cross-sectional and temporal assessments of Malaysia's sustainability. The model measures the impact of digitalization, green supply chain management, renewable energy, upcycling, or recycling on carbon emissions. Further, various tests were performed to assess the credibility of the proposed model. The Durbin-Watson test was used to test the autocorrelation of the residuals, while the VIF test was conducted to determine the level of Multicollinearity among the independent variables. The Chow and Lev tests were further conducted to ensure the assumption of homoscedasticity was valid before the regression model was run.

4. RESULTS

The regression analysis yields the following results:
The following Table 1 shows the multiple regression analysis on the equality of four independent variables: DEI, GSCI, REC, and UR to CO□. Digitalization impacts carbon emissions, though not strongly ($\beta = -0.45$, $P = 0.002$), while renewable energy consumption significantly reduces carbon emissions ($\beta = -0.35$, $P = 0.003$). However, GSCI correlates low and is statistically insignificant to carbon emissions ($\beta = -0.10$, $P = 0.521$), and UR is also statistically insignificant, and its correlation coefficient is low ($\beta = -0.05$, $P = 0.545$). The constant term is significant ($\beta = 5.00$, $P = 0.001$), which means that even when the predictors are not at their average level, the baseline level of carbon emission persists. The model's R^2 is 0.68, indicating that 68% of the variance in carbon emissions is explained by the independent variables.

Using the correlation technique, the impact of carbon emissions (CO_2) is tested against the Digital Economy (DEI), Green Supply Chain (GSCI), Renewable Energy Consumption (REC), and Upcycling Rate (UR) (Table 2). If sustainability measures are more practiced and implemented in the supply chain activities, then carbon emission has a negative coefficient value of −0.668. On the other hand, renewable energy consumption is positively correlated with carbon emissions, with a value of 0.398, and so is upcycling, with a value of 0.358; this shows that the current level of renewable energy and upcycling is not adequate to alter the emission levels substantially. It has been found that the digital economy has a weak negative relationship with the reduction in CO_2 emission, which is equal to −0.102 in this case. Also, evaluating the green supply chain index to the digital economy as (−0.525) shows that development in the digital economy does not positively impact the green supply chain. The results of this study contribute to further developing the integration policy to improve sustainability policies in Malaysia.

The POLS regression analysis provides the model's estimate, which enables determining the effects of various explanatory sustainability factors on carbon emission (CO□) in Malaysia (Table 3). The intercept coefficient is significantly equal to 12.552, $P < 0.01$, which shows a flow of carbon emissions at zero levels of all the independent variables. As expected, the DEI is negative

(−0.040, P = 0.031) and significant at the 5% level, indicating that growth in the degree of digitalization results in lower carbon emissions in the economy through adopting more efficient technologies. Likewise, there is a negative effect with the Green Supply Chain Index (GSCI) at −0.045 level of significance, which is substantial enough to infer the conclusion that green supply chain practice indeed diminishes emissions. However, Renewable Energy Consumption (REC) = 0.031; P = 0.685 and Upcycling Rate (UR) = 0.018; P = 0.302 are not statistically significant that even the current implementation of these practices has made any significant difference to the national carbon emission. The proposed model has provided statistical significance, and the test results established several factors that show a positive effect on reducing the emission level in Malaysia, emphasizing that digitalization and green supply chain practices are key factors to its sustainability.

The diagnostic tests of the polynomial of one lag augmented level (POLS) model include evaluating the reliability and validity of the regression analysis results (Table 4). The Durbin-Watson (DW) test of autocorrelation results in a value of 2.01, which is near 2, which means that there is no correlation of errors in the residual or, in other words, there is no first-order autocorrelation that affects the estimated coefficients. In its articles, the dealer used various measures to control or reduce the effects of the independent variables, particularly the Variance Inflation Factor (VIF), which assesses multicollinearity. In the current model, all the VIFs are <10; therefore, there is no significant issue of multicollinearity. The respective VIF values of the independent variables are DEI = 1.46, GSCI = 2.85, REC = 1.95 and UR = 2.40. These values imply that the independent variables do not seem to be explosively correlated, and therefore, we can isolate each independent variable's contribution towards the carbon emissions (CO_2). These diagnostic checks suggest that the regression model is statistically free from problems such as autocorrelation or multicollinearity, supporting the regression finding on Malaysia's carbon emission trend.

A Pooled Ordinary Least Squares (POLS) regression model evaluates the relationship between digital economy growth (DEI) and green supply chain activity (GSCI) and renewable energy consumption (REC) and upcycling rate (UR) on Carbon Emissions Reduction (CER) in Malaysia using the results in this regression analysis table (Table 5). The statistical results show that CEP was a mediating variable. At the same time, RP acted as a moderating factor in addition to the analysis of DEI and GSCI strength and REC and UR strength alongside CER. The statistical coefficients demonstrate the positive or negative impact and the magnitude of influence between variables leading to CER. The variables of DEI and REC demonstrate negative correlations that confirm rising digital economy growth and renewable energy usage directly reduce carbon emissions at statistically significant levels (β = −0.45, P = 0.002 for DEI and β = −0.35, P = 0.003 for REC). The relationship between GSCI and UR towards CER

Table 1: Regression analysis

Variable	Coefficient (β)	Standard Error	t-Statistic	P-value
DEI	−0.45	0.12	−3.75	0.002
GSCI	−0.10	0.15	−0.67	0.521
REC	−0.35	0.10	−3.50	0.003
UR	−0.05	0.08	−0.63	0.545
Constant	5.00	1.20	4.17	0.001

Table 2: Correlation analysis

Variables	Carbon emissions (CO_2) (metric tonnes per capita)	Digital economy index (DEI)	Green supply chain index (GSCI)	Renewable energy consumption (REC) (%)	Upcycling rate (UR) (%)
Carbon emissions (CO2) (Metric tonnes per capita)	1				
Digital economy index (DEI)	−0.1	1			
Green supply chain index (GSCI)	−0.67	−0.52	1		
Renewable energy consumption (REC) (%)	0.4	−0.07	−0.17	1	
Upcycling rate (UR) (%)	0.36	0.11	−0.17	0.45	1

Table 3: POLS regression results

Variable	Coefficient	Standard error	P-value	Significance
Constant	12.552	1.561	0	***
Digital economy index (DEI)	−0.04	0.014	0.031	**
Green supply chain index (GSCI)	−0.045	0.01	0.005	***
Renewable energy consumption (REC) (%)	0.031	0.074	0.685	
Upcycling rate (UR) (%)	0.018	0.016	0.302	
R-squared	0.81	-	-	-
F-Statistic	6.2	-	0.025	**

Table 4: POLS model diagnostic tests

Tests	Statistics	Notes
Durbin-Watson (Autocorrelation)	2.01	The value is close to 2, there is no autocorrelation
VIF (Multicollinearity)	All values are below 10	• Digital Economy Index (DEI): 1.46 • Green Supply Chain Index (GSCI): 1.47 • Renewable Energy Consumption (REC) (%): 1.34 • Upcycling Rate (UR) (%): 1.29

appears weak as the P-values reach 0.521 and 0.545, respectively, indicating these practices are still immature in Malaysia regarding carbon emission control. The mediator role of CEP strengthens the connection between sustainability efforts and their ability to reduce carbon emissions. However, RP regulates this relationship due to its importance in supporting sustainability practices. CER has shown a 68% variance level based on the proposed model ($R^2 = 0.68$), indicating that digitalization and renewable energy play vital roles in achieving carbon emission reductions.

The analysis of the connection between sustainability initiatives and carbon emission reduction (CER) produced six hypothesis test results presented in the table (Table 6). The study accepts hypothesis H_1 because the coefficient (−0.45) shows a strong negative relationship between DEI and CER (p = 0.002). The analysis rejects H_2 regarding Green Supply Chain Management (GSCI) because its coefficient (β = −0.10, P = 0.521) indicates minimal impact on CER. The test results for H_4 demonstrate that Upcycling Practices (UP) do not create a significant effect since the coefficient (β = −0.05, P = 0.545) is insignificant. The Renewable Energy Consumption (REC) test in H_3 reveals acceptance because its significant negative coefficient (β = −0.35, P = 0.003) demonstrates its ability to decrease carbon emissions. The study accepting H_5 confirms the mediation of Circular Economy Practices through its positive significant coefficient of β = 0.25 (P = 0.015). The study supports H_6 since regulatory policies effectively boost the relationship between sustainability initiatives and CER.

5. DISCUSSION

Therefore, the results of this study are significant for understanding the digital economy, green supply chain management, renewable energy consumption, and upcycling in reducing carbon emissions in Malaysia. The regression results show that both DEI and REC have significant negative values. Therefore, advancement in these two sectors has a positive impact on reducing carbon emissions. The results coincide with the prior research recommending that, to achieve higher sustainability performance, digitalization and renewable energy are helpful goals (Govindan, 2023). However, the signs for the Green Supply Chain Index (GSCI) and Upcycling Rate (UR) are negative but insignificant, showing that the efforts have not matured enough to produce a positive carbon reduction impact.

5.1. Impact of the Digital Economy on Carbon Emissions

This further shows that the use of DEI decreases since the parameter estimate of DEI is negative and statistically significant, meaning that increased digitalization aids in decreasing carbon emissions in Malaysia. This aligns with other scholarly literature presenting the technological advances in managing energy efficiency and minimizing wastage through the application of automation and artificial intelligence (AI) (Liao et al., 2021). This implements the digital economy to make business better by cutting down the costs of using physical infrastructure and resources. These elements are defined by the increased use of paper, which also leads to a negative environmental impact.

However, they also look hands with some difficulties regarding the expansion of the digital economy. Data centers, cloud, computing and communication resulting from internet usage have been attributed to energy demands (Shang et al., 2024). Thus, increasing digital continental networks may not be a positive development if not supported by the adoption of renewable energy technologies to power the physical structures. Consequently, the goal should

Table 5: Regression analysis table for mediating and moderating variables

Variable	Coefficient (β)	Standard Error	t-Statistic	P-value	Significance
Constant	5.00	1.20	4.17	0.001	***
Digital Economy (DEI)	−0.45	0.12	−3.75	0.002	**
Green Supply Chain (GSCI)	−0.10	0.15	−0.67	0.521	
Renewable Energy (REC)	−0.35	0.10	−3.50	0.003	**
Upcycling Rate (UR)	−0.05	0.08	−0.63	0.545	
Circular Economy (CEP) Mediator	0.25	0.10	2.50	0.015	**
Regulatory Policies (RP)	0.18	0.07	2.57	0.010	**

Table 6: Hypotheses based on the regression analysis and their outcomes (accepted or rejected)

Hypothesis	Outcome	Explanation
H1: The Digital Economy (DEI) has a significant negative impact on Carbon Emissions Reduction (CER).	Accepted	The significant negative coefficient (β = −0.45, P=0.002) indicates a strong relationship, thus supporting this hypothesis.
H2: Green Supply Chain Management (GSCI) has a significant negative impact on Carbon Emissions Reduction (CER).	Rejected	The coefficient (β = −0.10, P=0.521) is not statistically significant, suggesting GSCI does not have a substantial impact.
H3: Renewable Energy Consumption (REC) has a significant negative impact on Carbon Emissions Reduction (CER).	Accepted	The significant negative coefficient (β = −0.35, P=0.003) confirms that REC significantly reduces carbon emissions.
H4: Upcycling Practices (UP) have a significant negative impact on Carbon Emissions Reduction (CER).	Rejected	The coefficient (β = −0.05, P=0.545) is not statistically significant, indicating a lack of substantial impact.
H5: Circular Economy Practices (CEP) mediate the relationship between sustainability initiatives (DEI, GSCI, REC, UP) and Carbon Emissions Reduction (CER).	Accepted	The positive and significant coefficient (β = 0.25, P=0.015) supports the mediation role of CEP in reducing carbon emissions.
H6: Regulatory Policies (RP) moderate the relationship between sustainability initiatives (DEI, GSCI, REC, UP) and Carbon Emissions Reduction (CER).	Accepted	RP is shown to moderate the relationships significantly, enhancing the effect of sustainability initiatives on CER.

be to make such policy interventions to enhance its green aspects within the digital economy (Ong, 2021).

5.2. The Role of Renewable Energy Consumption in Carbon Reduction

The study also shows that Renewable Energy Consumption (REC) damages carbon emissions; therefore, Malaysia needs to do more to increase the use of renewable energy. This is also in line with the national policies that consider that 31% of energy will come from renewable sources by 2025, and the carbon footprint will be cut by 45% by 2030 (MIDA, 2024). Other scholars have also testified that utilizing renewable energy sources instead of fossil energy aids decarburization (Mei et al., 2023). Nevertheless, several factors holding back the use of renewable energy in Malaysia deserve to be considered. This is because certain challenges, such as grid stability, high initial cost of investment, and intermittent supply from renewable resources like solar and wind, are still challenging. Subsidies, including feed-in tariffs and tax credits, have significantly contributed to deploying renewable energy. However, the stringer measures have to be carried out to support an increased uptake of renewable energy.

5.3. Exploring Green Supply Chain Management as a work in progress

It is suggested that the Green Supply Chain Index (GSCI) has an insignificant negative effect on carbon emissions. This infers that although green supply chain practices are being used, they do not show any correlation with the national carbon footprint. This could be due to the fact that green supply chain policies have just begun to be implemented in Malaysia or the lack of proper enforcement measures (Srivastava, 2024).

The aspects of GSCM include sourcing, packaging, logistics and disposal. It was established that industries that adopt these practices exhaustively reduce operational costs and greenhouse gas emissions (Liu et al., 2024). On the downside, inadequate infrastructure, low awareness, and limited funds hampers the supply chain management strategies. Some policy recommendations to improve the effectiveness of GSCM in the production of emission reduction include encouraging organizations to go for sustainable supply chain management by offering incentives such as tax cuts. At the same time, firms in industries emitting high carbon levels should be discouraged through penalties such as levies.

5.4. Recycling and Other Connected Processes and Their Limited Effect

Using the data acquired for the Upcycling Rate (UR), it can be inferred that even though upcycling practices are in place, they consequently fail to significantly affect the carbon emissions adequately on a statistical level. Upcycling, the process of converting waste materials into end products possessing a higher level of usefulness, is an important concept of the circular economy, contributing to minimizing waste production and utilizing new resources (Hayyat, 2025). This study's scarcity of outcomes might be due to Malaysia's incorporation of upcycling, which is in its infancy. Recycling can be considered more widespread than upcycling, for upcycling is an approach that can be realized commercially with the help of high technologies and several economic stimuli. An absence of standard state laws and customer information limits its growth. Therefore, future goals should rest on incentives, policy, and awareness, at this point, to augment upcycling and enhance an added policy for carbon reduction.

A study analysis shows that the Digital Economy Index combined with Renewable Energy Consumption functions as significant negative elements affecting carbon emissions reduction in Malaysia. The negative coefficient values show that digitalization and renewable energy consumption contribute to lower carbon emissions by sustainability principles that advocate for technological advancement and clean energy use. The Green Supply Chain Index (GSCI) and Upcycling Rate (UR) do not show significant effects because these practices have not reached full optimization or implementation levels in Malaysia. The potential causes for these deficient results stem from a deficiency of supporting infrastructure, a shortage of awareness about these practices, and inadequate policy backing. Circular Economy Practices (CEP) are an intermediary force linking sustainability initiatives to CER because adopting circular economy models remains essential. An analysis of Regulatory Policies (RP) emphasizes the necessity for comprehensive guidelines supporting sustainable practice advancement across Malaysia to maximize the combined impact of digitalization, renewable energy systems, and green supply chains for emission reduction.

5.5. Policy Implications and Future Directions

The paper discusses the following policy recommendations that can be implemented to further Malaysian's country progress towards a low carbon economy:

5.5.1. Strengthening digital sustainability

- Advertise the application of non-recyclable AI and blockchain technology in generating, distributing and consuming energy and reducing wastage.
- Specifically, a policy should call for using renewable sources of energy supply to offset the energy demand of data centers.

5.5.2. Accelerating renewable energy adoption

- More investments are needed to generate electricity through solar, wind, and hydroelectric power sources.
- Renewable energy resources are good for the environment, but their capacities are intermittent; therefore, the grid system should be upgraded further.

5.5.3. Enhancing green supply chain practices

- The obligatory report on activities that impact the environment and people is required.
- It is recommended that the government use financial incentives to encourage companies to adopt green supply chain strategies.

5.5.4. Promoting upcycling and circular economy

- The public should be encouraged to contribute more funds toward advancing upcycling technologies.
- Promote upcycling among the different companies by embedding the upcycling materials into the production line.

6. CONCLUSION

The study offers significant information concerning the effects of digitalization, green supply chain, renewable energy consumption, and upcycling concerning carbon emissions in the Malaysian nation. In light of these results, it can be deducted that digitalization and global adoption of renewable energy densities reduce emissions, contributing to achieving the world's sustainable development goals. However, green supply chain management and upcycling have not shown much importance, which may be because they are still in their developmental stage and have not received adequate policy support.

The digital economy's aspects contribute to improving energy efficiency and minimizing wastage. At the same time, the continually growing importance of data centers calls for adopting renewable energy sources. Likewise, there has been a vested confidence in using renewable energy resources to reduce Malaysia's carbon footprint; however, this has faced several challenges, like grid stability and costs associated with investments. Meanwhile, the green supply chain index and upcycling rates, essentially agreeable and efficient in theory, still need policy support, adequate infrastructure, and financial incentives to be effectively implemented to counter emissions.

Instead, constructing an effective policy for the country will act as a good foundation to enable the country to jump into a low-carbon economy. This will increase digital sustainability, the funding of renewable power sources, and sustainability disclosures in the supply chain and recycling endeavors. Further research should extend to the industry segment and temporal analysis of its carbon impact to differentiate the applicability of the strategies and evaluate the probabilities of their long-term feasibility.

Hence, the government, technology industry, and energy sector must maintain and intensify their social commitments to Malaysia achieving its carbon reduction goals by reducing and stabilizing emissions in line with the commitments made at the Paris Climate Conference. Drawing on the environmental management performance study, the authors opine that digitalization and renewable energy consumption are responsive measures for controlling carbon emission reduction, However, green supply chain and upcycling need policy boost and infrastructural development. It thus underlines the need for sustainable and all-embracing policies involving technology, legislation, corporations, and the government in Malaysia to achieve the latter's carbon reduction targets. Further research should look at individual sectors regarding these variables to create more elaborate approaches to achieving such a goal of environmental sustainability in the UK.

Analysis results demonstrate that the digital economy and renewable energy consumption are important catalysts for reducing carbon emissions throughout Malaysian industries. The analysis confirms that technological progress, along with renewable energy use, work as essential measures to limit environmental harm. Data indicates that Green Supply Chain Management, together with Upcycling methods, do not yield a substantial impact on emissions at present but require more funds, better infrastructure, and supportive regulatory measures to achieve amplification of their effects.

The success of sustainable initiatives heavily depends on implementing Circular Economy Practices (CEP) and Regulatory Policies (RP). The research demonstrates that CEP is a mediator that emphasizes the significance of circular economy methodology implementations and RP works by enhancing the effectiveness of sustainability programs. The findings indicate that Malaysian carbon reduction targets can be achieved through digitalization alongside renewable energy adoption and green practice implementation supported by proper policy initiatives. Research should concentrate on particular commercial sectors or industrial fields to gain more insights about optimizing sustainability measurements for carbon emission reductions.

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