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Material Scarcity in Logistics: A Rationale for Technology Development Responsibilities

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ABSTRACT

Introduction: Alerts of imminent scarcity exist for some technological materials that are critical to logistics. The development of cutting-edge, high-performing technology depends on uncommon components. Since material scarcity can impede future improvements, it is a serious matter that needs to be addressed. However, the risk is often overlooked in the hurry to progress technology. It seems that a lot of innovators are not aware of the limitations on the supply of necessary resources and the possible consequences that could arise from them. This should be noted by technology developers, who should carefully consider the present shortages of technology metals in the industrial supply.

Objectives: This study aimed to ascertain how material scarcity in logistics impacts workers' rational technology development responsibilities. Material scarcity in logistics was found to have an impact on technology development.

Methods: The phenomenon of material scarcity is examined in the article from an ethical standpoint related to sustainable development. 77 managers responded and gathered from Malaysia's manufacturing industry of logistics at Malacca state.

Results: The outcome demonstrated how material scarcity in logistics might foster technological advancement in sustainable supply chains. As a result, sustainable logistics performance demonstrated consistency in overcoming material scarcity, decreasing inventory, which boosts productivity, advancing environmental initiatives into new product development, and lowering prices. Overall, this study found the factor analysis with both material scarcity in logistics and technology development showed significant improvement in the stages of logistics responsiveness with 0.813 respectively. As leaders in the innovation system, they can drive change in the direction of resource-conscious technological advancement.

Conclusions: The paper's conclusion offers suggestions for how companies might lead the way in logistics' sustainable management of essential commodities.

Keywords: Material scarcity, Logistics, Technology Development.

INTRODUCTION

Recent disruptions to the supply chain and industrial logistics of several exotic technology metals have brought resource scarcity—a well-known sustainability issue—to light. Concerns have been expressed over the availability of rare earth elements material resources in the future (MA Leon and T. Daphne, 2023). These commodities are called "critical" because of their substantial supply instability and importance to the economy and technology. Important parts are necessary for the design of high-tech items as well as for clean or resource-efficient technologies. The current scarcity of technical metals is fuelling discussions on resource-preserving innovation strategies.

In addition, the state of the business environment shapes the strategy for maintaining a sustainable supply chain to gain a competitive edge. Additionally, media and non-governmental organizations that influence the sustainability aspect of supply and logistics development reinforce organizations in studies of the global community (Araz, O. M., Choi, T.-M., Olson, D. L., and Salman, F. S., 2020). Businesses are increasingly expected to carry out their

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sustainability initiatives ahead of operations to include suppliers to fulfil consumers' requirements in sustainability expectations, claim Michael Anenburg, Sam Broom-Fendley, Wei Chen (2021). Industry practices are evolving to improve logistics performance through sustainability.

For the past forty years, resource depletion has been a constant source of concern for sustainability specialists and economists (Fahian Anisul Huq & Mark Stevenson, 2020). The idea of resource scarcity has been contested by economists on numerous occasions, yet it is undeniable that the industrial supply of raw resources is becoming increasingly limited. Many indicators point to the possibility that some of the major conditions that make material abundance possible, such as cheap energy costs, might not be true in the future. It will become more challenging to meet the growing demand due to geopolitical, environmental, and economic factors (J.L. Calderon, N.M. Smith, M.D. Bazilian, E. Holley, 2024).

There is a belief these days that material scarcity presents problems for the environment and the economy (Lee Park, C., Fracarolli Nunes, M. and Machuca, J.A.D., 2023). The US Environmental Protection Agency (EPA) states that "business as usual cannot continue" because of the "rapid rise in material use that has led to serious environmental effects" (EPA 2020). However, because our contemporary technologies have grown so reliant on necessary elements, it is not only the environmental risks that must be considered; there is also a serious risk to the welfare and prosperity of society. Many advances could stop if essential raw materials become unstable in price or disappear. One new industry that is immediately impacted is the renewable energy industry. Despite this, possible constraints on the supply of crucial logistics components have often been overlooked in the development of new products and technologies. For a long time, industrial product design has been impacted by the idea of purposeful obsolescence (Carrara, S., Bobba, S., Blagoeva, D., Alves, D., Cavalli, A., Georgitzikis, K.,& Christou, M., 2023).

As technology in the logistics sector advances, constraints on the availability of energy and raw materials must be taken into consideration (Lin, C.C. and Lu, C.S., 2021). The symptoms of material shortage, for instance, immediately impact industrial designers and engineers since they restrict their options throughout the design phase. They also have a significant impact on resource use at the same time. They choose which materials are used in products and in what quantities. Furthermore, the length of time people will maintain a product before switching to a new one is determined by its design decisions. Therefore, the field of design engineering has the potential to spearhead the shift toward resource efficiency.

OBJECTIVES

The Earth's lithosphere serves as a critical reservoir for mineral resources essential to building and operating technological infrastructure. Common base metals such as iron, aluminum, copper, zinc, and other alloying metals like tin, nickel, and chromium are indispensable to traditional technologies. In recent years, the term "technology metals" has gained prominence within the industry. While these elements were once considered of marginal technological value, they are now recognized as fundamental to the advancement of science and technology (Shuang-Liang Liu et al., 2023). Nearly every metal and metalloid in the periodic table has found modern technical applications.

Despite the growing importance of these elements, concerns about raw material shortages continue to escalate. Qin and Zhang (2022) highlight how localized shortages of raw materials exacerbate a broader global supply deficit. This has led to increasing discussions around the potential global depletion of raw material sources, particularly in logistics. However, a re-examination of the relationship between growth and scarcity suggests that industrial growth is not necessarily constrained by the availability of raw materials (Md Kashif GD et al., 2023). Even in the face of difficult access to materials, industries continue to pursue expansion. As A. McKinsey (2022) notes, industries tend to use the raw materials that are closest to the point of consumption, increasing the intensity of use as accessibility rises.

To address the looming challenge of resource scarcity, it is critical that the logistics industry adopt proactive measures before the effects fully materialize. Material scarcity, especially as it has been amplified by the COVID-19 pandemic, can severely impact the production and maintenance of technological systems. Furthermore, the unchecked exploitation of remaining natural resources may lead to significant environmental damage, including pollution and ecological destruction (Sarkis, J., Cohen, M. J., Dewick, P., & Schröder, P., 2020). Consequently, any reduction in

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material resources poses not only environmental risks but also threatens the operational efficiency and sustainability of organizations. Improving supply chain performance through sustainable practices is essential to overcoming these challenges.

Industries such as clean technology, electronics, aerospace, and automotive manufacturing are particularly dependent on a reliable supply of technology metals. The growing demand for these resources is largely driven by low-carbon energy technologies like wind turbines, fuel cells, thin-film solar cells, and electric vehicle batteries (Di Giuseppe M., Perry JC., 2021). Without these materials, clean technologies cannot function effectively or offer favorable cost-benefit ratios. The transition to a low-carbon economy could be significantly delayed by the impending shortage of critical minerals. A 2010 European Commission report identified fourteen raw materials as facing significant supply risk, underscoring the vulnerability of the EU economy to resource scarcity. Montani and Stagliano (2021) further describe this issue as a "subtle but further-reaching" concern—one that centers around the long-term availability of essential metals.

Another growing concern is the fate of essential components in high-tech equipment once they reach the end of their life cycles. These devices, often considered technological masterpieces, are typically composed of large-scale materials embedded with vital elements. With the rapid advancement of ICT and smart electronics, there is an anticipated rise in compact and lightweight consumer devices, which will likely contribute to massive and dispersed waste streams (MA Leon & T. Daphne, 2023). As a result, recovering crucial parts and metals from this e-waste will become increasingly difficult, posing a major challenge for recycling and resource reuse efforts (Al-Omran K., Khan E., Ali N., Bilal M., 2021).

Additionally, the global consumption of resources has increased at an unprecedented rate. According to the EPA (2020), humans today consume significantly more resources than in the past. This rising demand can primarily be attributed to two key factors: economic and population growth and the increased consumption of products and services. While technological innovation has made it possible to produce high-tech goods more efficiently and in smaller forms, it has not led to a reduction in total resource consumption. Modern technology—though it enhances productivity through mechanisms like miniaturization—has inadvertently contributed to higher aggregate consumption. Ammendolia et al. (2022) argue that the industrialized global economy is largely responsible for this spike in natural resource usage.

In conclusion, the growing dependence on technological metals and other essential resources presents significant challenges for industries, governments, and societies worldwide. While technological progress drives efficiency, it also accelerates the consumption of finite resources. To ensure long-term industrial growth, environmental sustainability, and economic resilience, it is crucial to implement proactive strategies in resource management, enhance recycling technologies, and rethink global logistics and supply chain models.

METHODS

The study then included concerns about resource scarcity, with an emphasis on the environment, economic development, and technological advancements in the logistics industry. As a result, the firm representative responsible for operation management, purchasing, production, warehousing, logistics, and material packaging will be the most suitable respondent. Therefore, the questionnaire will be sent to the departments of supply chain and logistics management, purchasing, and distributors, who are typically from the purchasing, material engineering, and logistics departments of the manufacturing industry. Statistics will be used to analyze the data. Quantitative research techniques using the Statistical Package for the Social Sciences (SPSS).

Data on the mean, standard deviation, and factor analysis that are derived from those categories for the environmental, economic, and social outcomes are further examined by descriptive analysis, reliability testing, and regression analysis using Cronbach's Alpha. The questionnaire survey was used to collect the primary data. The questionnaire is divided into three components. The first portion asks for general information that is needed to determine the respondent profile. The question about material scarcity in logistics is found in the second section, and items on technology development responsibilities indicators are found in the final section.

The scales were chosen to assure validity and reliability in the research and are derived from well-established studies. A five-point Likert-type scale was employed; any number of points may be used, but a five-point scale, ranging from Strongly Disagree (1) to Strongly Agree (5), is frequently used to assess how well sustainable supply chain procedures affect the logistics performance of the company. Material scarcity was taken from Paul T. Mativenga et al. (2017), while the questionnaire model for sustainable supply chain and logistics performance was modified from Harmon and Cowan (2009).

The survey was conducted based on an individual sample unit and the survey was sent to the supply chain and logistics professionals. Contacts were gathered earlier to survey the convenience sampling technique as the sample involved supply chain and logistics professionals at different levels, such as managers, directors, or supervisors of different industries. To have better generalizability, the mail-carrying survey descriptions and links were sent to potential respondents from industries in Malaysia. The population of the study consisted of 300 manufacturing firms in Malaysia's manufacturing sector. Ages range from 27 to 55, and the study's unit of analysis is the executives and managers of a manufacturing company. The logistics industrial level in each company is the focus of the study because it is about material scarcity resource managing 77 respondents were gathered for the current study using the systematic sampling technique, which yielded 77 as the appropriate sample size according to the sample size calculation. A sampling method known as systematic sampling selects a sample from a larger population regularly (Hayes, 2022).

The study's data came from Malaysian manufacturing companies. The focus of this study was upper management from several manufacturing companies in the Southern Region. Additionally, it is considered necessary to have a sampling frame to conduct an effective cluster sampling procedure. Random selection is used to choose clusters from a sampling frame, which can be laborious and ineffective. These provinces suggest that other manufacturing developments and market economies would have been more appropriate.

Data was gathered using accessible sampling, and the sample size was limited by the industry's time constraints resulting from their scheduling and working hours of required travel for logistical tasks. As a result, responses to the questionnaire were sent via email, WhatsApp, Telegram, and Google Forms. Factor analysis and reliability tests were utilized in the quantitative research designs to validate the findings and support or refute a hypothesis.

This study used a pilot test, and based on the respondent's response rate, a valuable means from the testing procedures for this research measurement was established. A total of 300 people were asked to participate in the survey, which was conducted in the Southern Region of Malaysia. Of those, 77 respondents have returned in each state, covering the manufacturing of food products, beverages, machinery, electrical and electronic goods, transport equipment, engineering support, building materials, textiles, chemicals and pharmaceuticals.

Data examination toward separating information from different resources of information gathered from the Material Structural Scarcity resource in the Logistics and Technology development responsibilities area and analysed with assistance from SPPS programming.

Questionnaires are used as a structure to aim for the quantitative survey, which is to collect data and assess changes in the data acquired. This study used a quantitative research method instrument survey. Utilizing statistics and an experimental design based on the instrument used for data collection, analysis, and measurement, the study makes use of the Statistical Package for the Social Sciences (SPSS). Factor analysis is employed in this study to verify that the items in each segment load into the anticipated categories. Furthermore, Cronbach's alpha was employed to evaluate the homogeneity or internal consistency of the items.

RESULTS

The exploratory factor analysis with Varimax rotation was accomplished to validate the assessment and appropriateness of the measurement scale. With eigenvalues greater than 1.00 the total variance explained was 61.28%. The Kaiser-Meyer-Olkin measurement of sampling adequacy (KMO-MSA) measure of sampling adequacy was 0.758 indicating sufficient intercorrelation while Bartlett's Test of Sphericity was significant (Chi-square 1.5901, $p < 0.001$), therefore factor analysis can be considered as appropriate. Items with factor loading greater than 0.30 were retained. The result shows with cheap and easy access to raw materials, a company can produce more of its

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goods at a lower cost. Consequently, the product is more widely available on the market. Production costs, however, will increase if raw materials are costly or hard to come by. Non-renewable resource depletion is one of the main issues with raw materials. Once depleted, non-renewable resources like oil and natural gas cannot be regenerated since they are limited. The rapid depletion of these resources is a result of the increased demand for them. There were 10 questions on material scarcity in logistics, and one factor was extracted (Table 1).

Table 1

Factor analysis for material scarcity in logistics

Items	Items no.	Factor
		SS
Material scarcity		
Build up inventories (just-in-time)	SS1	**0.750**
Testing alternative raw materials	SS2	**0.740**
Environmental initiatives advance product innovation	SS3	**0.720**
Hedging purchase prices	SS4	**0.700**
Sustainable products give us a competitive edge	SS5	**0.690**
Conducting price negotiation	SS6	**0.600**
Implementation of procurement cooperation	SS7	**0.899**
Relocation of the facilities to other countries	SS8	**0.751**
Volume shifting from existing suppliers	SS9	**0.720**
Cooperation with customers in the procurement	SS10	**0.880**
KMO		0.758
Bartlett's Test of Sphericity		1.5901
Eigenvalue		3.988
Percentage variance (61.28%)		22.818
Sig. p-value		0.001

Table 2 displays the results of the factor analysis for the technology development responsibilities. According to the main theoretical framework, resources with material scarcity have a greater influence on technology development responsibilities. Three distinct elements, however, are identified by the factor analysis results as the consequences' effects. The potential effects of material scarcity issues in supply chain and logistics sustainability management can be classified as the economic, environmental, and social effects, according to a McKinsey (2022) survey of the literature on the subject. Furthermore, these outcome categories were compared to the technology development responsibility management outcome that Majumdar et al. (2020) proposed.

This outcome framework classified sustainable supply chain outcomes as social, economic, and environmental outcomes, all of which are closely related to sustainable technology development. referring to the questions that Harmon and Cowan (2009) developed based on the concept of material scarcity in logistics frameworks. The results of the Varimax rotation were used to validate that there are constructs distinctive in technology development responsibility. Results showed three clarifications with eigenvalues greater than 1.0 and the total variance explained was 71.33%. The measurement KMO of sampling adequacy is 0.619 indicating sufficient intercorrelation, while Bartlett's Test of Sphericity was significant (Chi-square 2.2211, $p < 0.001$). As economic systems become more complicated and diverse, one of the main problems is the development of logistics technology. The secret to success and minimising the expenses related to the process of implementation and the ensuing use of solutions is the creation

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of suitable guidelines for the application of these concepts. Owing to its critical role in the operation of cities and, by extension, the economy as a whole, it is a crucial field of study in the application of sustainable development. This result confirms that the construct is unidimensional and particularize distinctively and that all the items used to measure a particular construct are loaded on three factors (Table 2).

Table 2

Factor analysis for technology development in logistics

Items	Items no.	Component EN	ECO	SOC
Economics (ECO)				
The delivery transport cost in the overall cost of the supply chain	ECO1	**0.635**	0.282	0.115
The volume of freight brought into the urban area	ECO2	**0.613**	0.287	0.272
Wages in urban freight transport	ECO3	**0.581**	0.165	0.629
Load capacity utilization	ECO4	**0.669**		
Environment (EN)				
Typical fuel consumption by vehicle category	EN1	0.191	**0.671**	0.157
Energy consumption in urban freight transport	EN2	0.282	**0.613**	0.238
Share of urban freight transport in exhaust emissions	EN3	0.190	**0.611**	0.104
Social (SOC)				
The weekly schedule of accidents involving trucks	SOC1	0.072	0.090	**0.657**
The number of drivers of commercial vehicles and trucks	SOC2	0.209	0.067	**0.530**
Share of freight vehicles in accidents	SOC3	0.078	0.275	**0.612**
KMO		0.619		
Bartlett's Test of Sphericity		2.2211		
Eigenvalue		2.725	2.635	2.901
Percentage variance (71.33%)		21.712	19.009	18.099
Sig. p-value		0.001		

As technology advanced, the initial theories regarding the connections between material scarcity and results in logistics were confirmed, despite changes in the theoretical framework. The inclusion of environmental, economic, and social variables in the measurement's expanded list is reflected in the reaffirmed hypotheses. As a result, additional theories were introduced to represent the proposed connections between the logistics of material scarcity and the predicted results in the areas of the environment, the economy, and society. Consequently, it is established that there is a theoretical basis for including this article in the management literature.

Figure 1: Modified Theoretical Framework

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All significant variables' reliability was assessed using Cronbach's alpha, which measures the consistency of an item to another. The values of the variables used in this study were calculated using Cronbach's alpha (), the most widely used indicator of internal consistency. All variables' values were deemed to be preferable and reliable if they were greater than 0.70. According to research, the micromanage leadership style had the lowest Cronbach's alpha (0.751) and the value in employee perception had the highest (0.899). The fact that all variables considered have high Cronbach's alpha values suggests that the test items are trustworthy and dependable. This is because every question on the survey was either taken directly from, or modified from, previously published journals or articles that had undergone empirical testing.

Table 3 displayed the multiple regression analysis's findings. They were employed to evaluate the effect on a dependent variable of a set of independent variables. For example, what proportion of the variance of the dependent variable can be explained by the collection of independent variables.

Table 3: Reliability analysis of overall construct

Variable	No of Items	Cronbach's Alpha (α)
Overall	**20**	**0.813**
Material Scarcity in Logistics (IV)	10	0.721
Economic in Technology Development Logistic	4	0.769
Environmental in Technology Development Logistics	3	0.788
Social in Technology Development Logistics	3	0.809

Table 4 presents the results of the regression analysis for material scarcity logistics and technology development responsibility. The first model is between material scarcity logistics and environmental in technology development responsibility and it was significant (F=21.535; p<0.001) with R2=0.447 and adjusted R2=.420. Moreover, material scarcity logistics was significantly related to economics in technology development responsibility (β=.481, p<0.001). The next model is between material scarcity logistics with social technology development responsibility. This model can explain 41.1% (R2=0.425) of the variance on economic performance and was significant (F=21.781, p < 0.001). The 58.6% due to error or explained by other factors are not included in this study. Material Scarcity in Logistics (β=.481, p<0.001) was found to be statistically related to economic performance in technology development responsibility. Therefore, the result it shows that the significant value is less than 0.05, which is between the Structural Scarcity component and sustainable supply chain performance with a p-value<0.001 makes the variable in a significant unique contribution to the prediction of the variable. Thus, the result for H1, H1a, H1b and H1c material scarcity logistics will be significant in improving technology development responsibility is supported for this study.

Table 4

Regression of material scarcity logistics on technology development responsibility

Material Scarcity Logistics	**Environmental** **β**	**Economic** **β**	**Social** **β**
Structural Scarcity	0.671	0.481	0.411
R^2	0.447	0.317	0.425
Adjusted R^2	0.420	0.331	0.409

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F	21.535	37.881***	21.781***

Significant Level:
**p <0.01.
*** p < 0.001.

Based on the findings, material scarcity in logistics has a favorable impact on social, economic, and environmental performance in the duty of technological advancement. Furthermore, according to the main theoretical framework, material scarcity in logistics is related to the outcomes of measuring sustainable technological development. As a result, the performance of sustainable logistics demonstrated consistency in overcoming material shortages, decreasing inventory, which boosts productivity, advancing environmental activities into product innovation, and cutting costs. As a result, the timely delivery of the product to meet customer demand demonstrates that consistent performance is typically attributed to sustainable supply chain performance in products that have been implemented in the Southern Region of Malaysia's manufacturing industry. The factor analysis in the procurement cooperation implementation with 0.899 revealed that the sustainable logistics on technology development greatly improved in the manufacturing stages, increased product diversity, decreased manufacturing cost, increased market share, introduced new products quickly, and were at the forefront of future legal requirements.

DISCUSSION

The results of factor analysis reveal four distinct drivers influencing outcomes related to material scarcity and logistics performance. These factors were grouped and analyzed about the responsibilities of sustainable technology development, aligning them with the environmental, economic, and social dimensions of sustainability. The findings suggest that the environmental performance of technological development is reflected in positive impacts such as improved compliance with environmental regulations, reduced exposure to material-related hazards, and decreased energy consumption—particularly important when resources are limited.

On the economic front, successful technology development is characterized by increased financial returns, greater market share, reduced waste disposal costs, enhanced efficiency in resource management, and improved sales performance. From a social perspective, the responsibility of technology development is demonstrated through enhanced product conceptualization and alignment with customer perceptions regarding the scarcity of materials. However, the simultaneous limitation in the supply of several essential raw materials further complicates the identification of viable alternatives. Supply shortages—often unpredictable—can act as a constraint on innovation, stifling technological advancement.

Despite these challenges, feedback from firms indicates that initiatives focused on sustainable technology development may benefit a range of stakeholders, both internal and external. These include suppliers and customers, particularly concerning the dynamics of supply and demand. Although the core challenge in logistics lies in managing material scarcity to enhance sustainability, firms are also faced with declining reserves of raw materials. By assuming greater responsibility in sustainable technology development, organizations can create indirect value for both suppliers and customers, thereby contributing to broader improvements in logistics performance.

Moreover, this study contributes to the body of knowledge by highlighting the importance of regular Key Performance Indicator (KPI) monitoring. A lack of such monitoring can hinder an organization's ability to effectively address material shortages across environmental, economic, and social domains. The findings from this study specifically underscore the influence of material scarcity logistics on the Malaysian manufacturing sector. A positive correlation was observed between factors related to material scarcity logistics and the organizational responsibility for sustainable technology development, affirming the importance of integrated strategies for long-term operational performance.

One of the critical challenges in anticipating future raw material availability is the inherent unpredictability of emergent events within economic and technological systems. Unlike in previous eras, many aspects of modern civilization—such as unprecedented population density, accelerating climate change, and the approach of peak oil—have no historical parallels. This makes it difficult to draw upon past trends to forecast future outcomes accurately. In this context, the value of speculative predictions is limited; instead, the emphasis should be on building adaptive and resilient systems that can accommodate uncertainty and scarcity.

This study explores how Malaysian manufacturing companies manage material scarcity in logistics and how it impacts their responsibilities in sustainable technology development. With growing global awareness of sustainability, businesses are increasingly focused on integrating sustainable practices into supply, demand, and transportation strategies. Managing resource scarcity through technological innovation can help reduce costs, improve product development, and enhance environmental, economic, and social performance. However, uncertainties in socioeconomic conditions and societal priorities, along with political and environmental disruptions, can influence resource availability and market dynamics.

The study also highlights the importance of addressing both intergenerational and intragenerational justice. While intergenerational justice ensuring current actions do not harm future generations remains an ideal, real-world progress may depend more on present generations acting in their long-term interest. As material scarcity begins to affect current prosperity, the need for sustainable practices becomes more urgent and personally relevant.

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