GREEN SUPPLY CHAIN TRANSFORMATION IN MINING SERVICES: A HYBRID CONCEPTUAL EMPIRICAL STUDY OF BATTERY ELECTRIC MINING DUMP TRUCK ADOPTION IN INDONESIA

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Abstract

The mining services industry in Indonesia is under growing pressure to adopt more sustainable operational practices in response to shifting environmental expectations, tightening regulatory demands, and evolving client requirements. Diesel powered haulage systems remain the dominant contributor to greenhouse gas emissions and cost inefficiencies within the mining supply chain. This study investigates how Battery Electric Mining Dump Trucks (BEMDT) can serve as a catalyst for green supply chain transformation in large-scale coal mining operations. Drawing on a qualitative case study approach supported by the Triple Bottom Line framework, the research incorporates operational observations and relevant literature to examine the feasibility, benefits, and barriers associated with BEMDT adoption. The findings reveal that electrifying haulage operations offers substantial environmental benefits through reduced emissions, alongside long-term economic gains driven by lower energy and maintenance costs. The transition also enhances alignment with the sustainability commitments of mining principals pursuing Net Zero pathways. However, challenges persist, particularly related to capital requirements, charging infrastructure, workforce readiness, and policy uncertainty. The study proposes a conceptual model that integrates electrification within the broader Green Supply Chain Management framework. The model provides both theoretical contributions and practical guidance for mining contractors seeking to enhance sustainability performance in emerging market contexts.

Keywords: *Battery Electric Mining Trucks, Green Supply Chain Management, Sustainable Operation, Triple Bottom Line, Indonesia.*

1. INTRODUCTION

Mining remains one of Indonesia's most strategic and economically significant sectors, contributing substantially to national income, employment, and energy security. Despite its economic importance, the sector faces increasing scrutiny due to its environmental footprint, including greenhouse gas (GHG) emissions, land degradation, and resource-intensive operations. As global pressures intensify, mining companies are expected to demonstrate stronger commitments to sustainability and align their operations with Environmental, Social, and Governance (ESG) principles. This expectation extends beyond mine owners to mining service contractors, who operate the majority of heavy equipment fleets and therefore shape a large portion of supply chain environmental performance.

Within academic discourse, Green Supply Chain Management (GSCM) has become an essential framework for improving environmental performance across various industries. Early works by Sarkis (2003), Zhu & Sarkis (2004), and Srivastava (2007) emphasize that GSCM requires organizations to integrate environmental considerations into procurement, production, logistics, and distribution activities. More recent studies extend this concept to heavy industries, highlighting that sustainable supply chain transformation increasingly depends on technological innovation and system-wide collaboration rather than isolated interventions.

In the mining sector, scholarly attention has grown around two major themes: low-carbon operations and technological decarbonization. Research by Laurence (2011), Azadi et al. (2020), and Lotz (2023) underscores that mining activities are among the most resource-intensive and carbon-intensive industrial processes. Among operational stages, haulage systems—dominated globally by diesel-powered dump trucks—represent the single largest contributor to direct emissions. Studies from Australia, China, and Sweden have begun documenting the role of Battery Electric Mining Dump Trucks (BEMDT) in reducing operational emissions, demonstrating reductions between 40% and 80% depending on duty cycles and energy sources (Xiao et al., 2021; EPRI, 2022).

However, the literature also identifies substantial implementation barriers. Prior research highlights challenges including charging infrastructure limitations (Mills, 2020), high initial investment (Schmidt et al., 2019), workforce adaptation (Abraham & Knight, 2021), and geographical or climatic constraints that affect battery performance (Nyberg et al., 2022). While these studies offer valuable insights, they predominantly focus on mature mining jurisdictions with advanced energy infrastructure and high regulatory pressure.

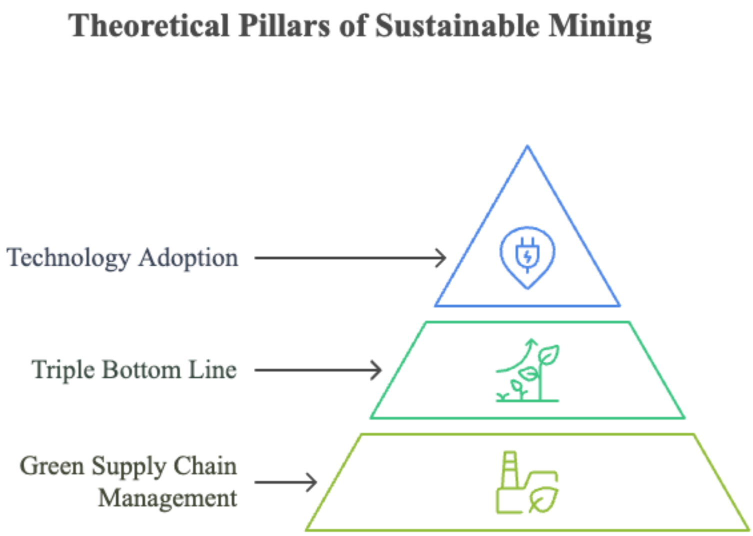
There remains a significant research gap regarding how electrification technologies can be adopted within emerging markets, particularly Southeast Asia, where mining operations occur in remote, humid, and geographically diverse environments. Indonesia represents one such context. Although research has explored the country's environmental challenges, carbon footprint, and ESG drivers (Liu et al., 2020; Widodo et al., 2022), little empirical or conceptual work has examined how mining contractors—rather than mine owners—can support supply chain decarbonization.

This gap is consequential. In practice, mining contractors play a central role in Indonesia's mining business model. They operate most of the haulage fleets, manage day-to-day logistics activities, and contribute significantly to Scope 1 emissions within mining supply chains. Yet, contractor-focused sustainability transformation remains largely absent from academic literature. Existing studies on green mining in Indonesia tend to focus on policy, land rehabilitation, or environmental governance rather than operational technology transitions.

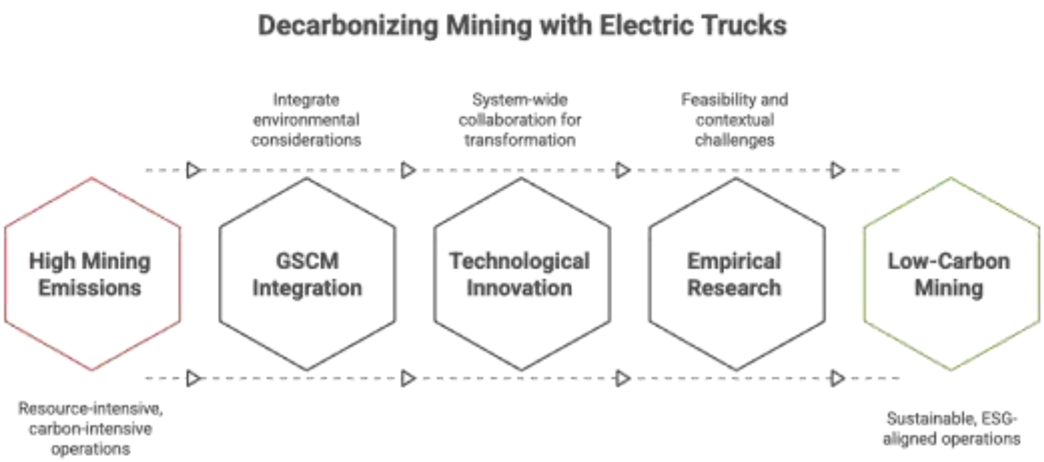
The present study addresses this gap by investigating how BEMDT adoption can support green supply chain transformation among mining contractors. Situating the analysis within the GSCM and Triple Bottom Line (TBL) frameworks, the research examines environmental gains, economic feasibility, and social implications associated with electrifying mining haulage. The TBL framework (Elkington, 1997) provides a multi-dimensional lens, enabling a holistic assessment beyond purely technical or financial considerations.

Conceptually, this paper synthesizes insights from GSCM, sustainable operations, and low-carbon technology adoption to propose a hybrid conceptual–empirical model for mining contractor decarbonization. Empirically, the research draws on operational observations and secondary data from Indonesian coal mining operations to illustrate feasibility and contextual challenges. This hybrid structure responds to calls from scholars such as Seuring & Müller (2008) and Köhler et al. (2019) to combine theory-building with evidence-based insights, especially in emerging economies where empirical data may still be limited but transformation imperatives are urgent.

2. THEORETICAL BACKGROUND



The transition toward low-carbon and sustainable mining operations requires a comprehensive understanding of the theoretical frameworks that underpin environmental management, technological adoption, and supply chain transformation. This section elaborates on three major theoretical pillars relevant to this study: Green Supply Chain Management (GSCM), the Triple Bottom Line (TBL), and technology adoption frameworks related to



electrification in heavy industries. Together, these theories provide the conceptual basis for examining how Battery Electric Mining Dump Trucks (BEMDT) can support sustainability-oriented supply chain transformation within the mining services sector.

2.1 Green Supply Chain Management (GSCM)

Green Supply Chain Management has evolved as a critical field within operations and environmental management, emphasizing the need to integrate ecological considerations into traditional supply chain activities. Early work by Sarkis (2003) and Srivastava (2007) positions GSCM as a strategic approach that aligns environmental performance with operational efficiency. GSCM practices span upstream activities, such as green procurement and supplier environmental collaboration, to downstream processes, including eco-friendly logistics and end-of-life management.

In mining, GSCM has gained relevance as scholars recognize that environmental performance is shaped not only by mine owners but also by their contractors and equipment operators. Zhu and Sarkis (2004) demonstrate that the adoption of environmental practices across supply chain actors results in cumulative sustainability benefits. More recent studies expand GSCM's scope to include digital technologies, energy transition mechanisms, and regulatory pressures influencing sustainability adoption in resource-intensive industries. This theoretical lens situates BEMDT adoption as a supply chain intervention capable of improving environmental outcomes across mining operations.

2.2 Triple Bottom Line (TBL) Framework

The Triple Bottom Line, introduced by Elkington (1997), provides a multidimensional framework for evaluating sustainability performance across environmental, economic, and social dimensions. Within industrial and extractive sectors, TBL has been adopted as a guiding framework for assessing operational practices beyond short-term financial metrics. The environmental dimension emphasizes reducing emissions, resource consumption, and waste generation. The economic dimension focuses on efficiency, competitiveness, and long-term financial viability. The social dimension highlights worker welfare, community impact, and broader societal well-being.

In the context of electrifying mining haulage systems, the TBL framework enables holistic evaluation: environmental benefits relate to emission reductions and improved air quality; economic benefits stem from lower energy and maintenance costs; and social benefits arise through safer, cleaner work environments and enhanced stakeholder trust. Prior mining sustainability studies (Laurence, 2011; Azadi et al., 2020) acknowledge the relevance of the TBL approach in examining operational innovations that shape long-term sectoral resilience. The TBL framework therefore provides a robust foundation for analyzing BEMDT adoption as a sustainability-driven technological shift.

2.3 Technology Adoption in Heavy Industrial Systems

Technology adoption theories offer additional insights into how organizations incorporate novel systems such as electrified heavy equipment. The Diffusion of Innovations theory (Rogers, 2003) suggests that technological transitions require both perceived relative advantage and compatibility with existing operational practices. In mining, the relative advantage of electrified trucks depends on measurable improvements in efficiency and sustainability, while compatibility relates to infrastructure readiness, operator skills, and site-specific operational characteristics.

Complementary frameworks such as the Technology–Organization–Environment (TOE) model explain how adoption is shaped by organizational capabilities, technological feasibility, and external pressures, including regulatory mandates and market expectations. Studies in industrial decarbonization (Schmidt et al., 2019; Nyberg et al., 2022) highlight that successful adoption of electric heavy vehicles requires supporting infrastructure, workforce readiness, and long-term financial justification. Within mining operations, additional barriers emerge from remote locations, harsh environmental conditions, and the capital-intensive nature of fleet transitions. These frameworks collectively underscore that BEMDT adoption involves not only technological readiness but also organizational commitment and contextual adaptability.

2.4 Integration of GSCM, TBL and Technology Adoption Frameworks

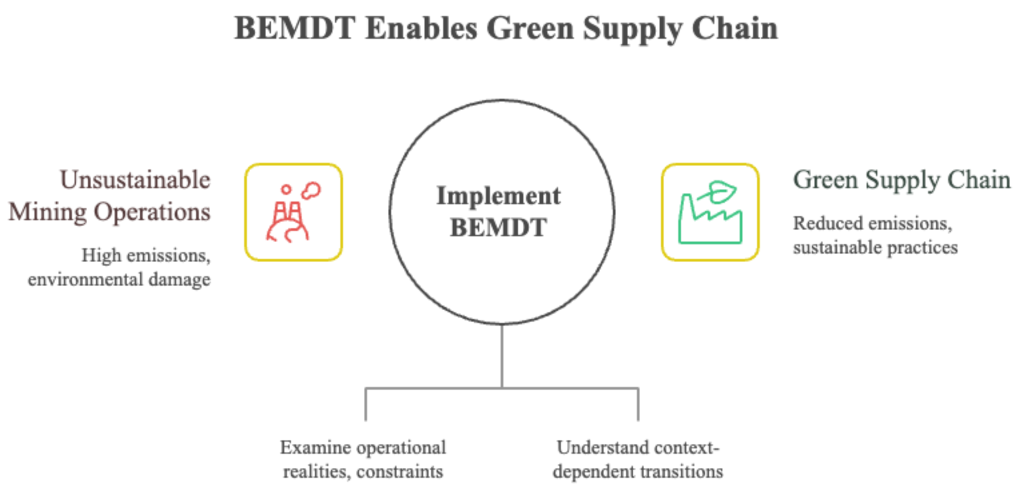
The convergence of GSCM, TBL, and technology adoption theories provides a structured basis for examining how mining contractors can transition toward greener operational models. GSCM emphasizes supply chain-wide environmental responsibility, TBL creates a multidimensional assessment lens, and technology adoption theories explain the enabling conditions required for implementing electrification technologies. Integrating these frameworks supports a comprehensive analysis that captures environmental benefits, economic rationality, and social implications, while recognizing systemic barriers and organizational constraints.

This integrated theoretical foundation allows the present study to conceptualize BEMDT adoption as both an operational innovation and a strategic transformation mechanism capable of restructuring mining supply chains toward more sustainable trajectories. It positions mining contractors not merely as operational entities but as pivotal actors capable of driving Indonesia's mining decarbonization agenda.

3. METHODOLOGY

This study adopts a qualitative exploratory case study design to examine how Battery Electric Mining Dump Trucks (BEMDT) can enable green supply chain transformation within Indonesian mining services. The methodological approach is grounded in the view that sustainability-oriented technological transitions in emerging markets are complex, context-dependent, and embedded within broader socio-technical systems. As such, qualitative inquiry offers an appropriate lens for unpacking operational realities, organizational constraints, and systemic enablers associated with electrifying mining haulage.

3.1 Research Design



A qualitative case study approach was selected to enable in-depth analysis of a mining contractor operating within Indonesia's coal industry. Case study designs are well-suited for exploring contemporary phenomena within real-world settings, particularly when boundaries between the phenomenon and the context are not clearly defined (Yin, 2018). This approach aligns with prior studies on green supply chain transformation and industrial decarbonization, which emphasize the need to capture operational complexity, stakeholder perspectives, and site-specific constraints.

The case is representative of typical Indonesian mining contractor operations, characterized by large diesel-based hauling fleets, remote site conditions, and evolving sustainability pressures from clients and regulators. Although the case does not aim for statistical generalization, analytical insights are expected to contribute to theoretical understanding of GSCM adoption and low-carbon technology transitions in emerging market contexts.

3.2 Conceptual Framework

The analysis is guided by an integrated conceptual framework combining Green Supply Chain Management (GSCM), the Triple Bottom Line (TBL), and technology adoption theories. These frameworks collectively inform the analytical categories used to evaluate the feasibility and sustainability implications of BEMDT adoption.

- GSCM provides the supply chain perspective by identifying environmental touchpoints and opportunities for greener operations.
- TBL enables a multidimensional assessment of environmental, economic, and social impacts.
- Technology adoption models (including Diffusion of Innovations and TOE frameworks) support evaluation of organizational readiness, infrastructural requirements, and external drivers influencing adoption.

This integrated structure allows the study to assess not only environmental gains but also operational, financial, and workforce-related implications.

3.3 Data Collection

Data were collected from multiple sources to support triangulation and enhance internal validity. These sources include:

1. Operational Observations
   Field based observations were conducted at Indonesian coal mining sites to examine current haulage operations, fuel consumption patterns, equipment utilization, maintenance routines, and site infrastructure conditions. These observations allow assessment of the operational baseline against which electrification scenarios can be evaluated.
2. Document Review and Secondary Data
   Company reports, equipment specifications, sustainability reports, government policy documents, OEM technical publications, and industry datasets were reviewed. Peer-reviewed literature relating to GSCM, mining sustainability, electric haulage technology, and industrial decarbonization was also analyzed to substantiate findings and contextualize Indonesia within global trends.
3. Expert and Practitioner Insights
   Informal consultations were conducted with engineers, fleet managers, sustainability specialists, and procurement personnel familiar with mining contractor operations. These insights helped validate assumptions regarding infrastructure feasibility, cost structures, and workforce implications.

Data triangulation strengthens the analytical robustness and provides a holistic understanding of feasibility, challenges, and opportunities associated with BEMDT adoption.

3.4 Data Analysis Approach

Data were analyzed using a thematic analytical process. This involved coding and categorizing information into themes corresponding to the conceptual framework: environmental impact, economic feasibility, social implications, supply chain effects, and adoption challenges.

The analysis proceeded in three stages:

1. Baseline Characterization
   Mapping current diesel-based operations to quantify environmental and economic impacts.
2. Comparative Assessment
   Evaluating potential benefits of BEMDT adoption relative to the diesel baseline, using both literature benchmarks and operational assumptions grounded in field observations.
3. Sustainability Interpretation through TBL and GSCM
   Interpreting findings within the TBL and GSCM frameworks to assess multi-dimensional sustainability outcomes and supply chain implications.

This structured approach supports rigorous interpretation while accommodating context-specific considerations typical of emerging market mining operations.

3.5 Scope and Limitations

The study focuses on contractor-operated haulage systems within Indonesian coal mining environments, which represent a major portion of supply chain emissions but also a segment with limited academic scrutiny. As an exploratory study, the analysis relies on secondary data, operational observations, and literature rather than primary quantitative measurements. While this limits statistical generalizability, the approach remains valuable for theory-building and conceptual expansion regarding green mining supply chains in emerging markets.

Future empirical research could build on this foundation through simulation modelling, cost benefit quantification, or pilot project performance tracking to produce more granular insights.

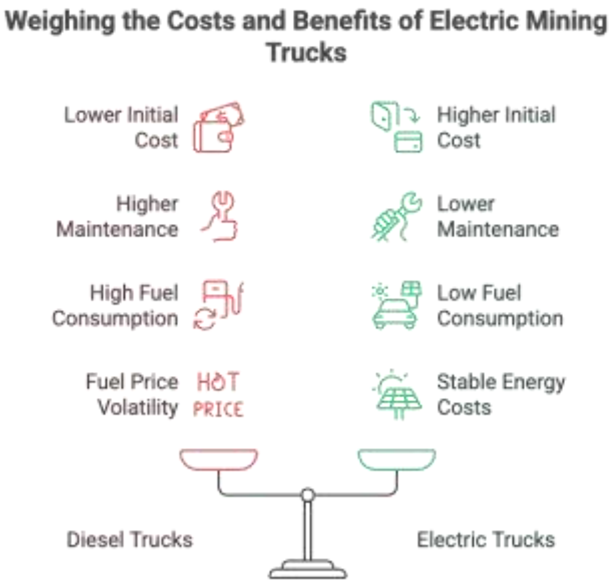
4. RESULT AND DISCUSSION

4.1 Environmental Performance Improvement through BEMDT Adoption

The analysis demonstrates that electrifying haulage operations offers substantial environmental advantages compared with diesel-based systems. Observational data indicate that a typical 100-ton diesel mining truck consumes approximately 80–90 liters of fuel per hour and operates up to 20 hours per day. Aggregated across a fleet, annual emissions exceed 300,000 tons of CO_2 for a single contractor. This aligns with figures reported in international literature, which identifies haulage as the dominant contributor to Scope 1 emissions in open-pit mining (Azadi et al., 2020; Lotz, 2023).

The adoption of BEMDT significantly reduces carbon intensity. Depending on the operational duty cycle and electricity source, emission reductions range between 50% and 80%. If renewable energy is integrated into site operations, emissions approach near-zero levels. In addition to carbon reductions, BEMDT eliminate local air pollutants such as NOx, SO_x, CO, and particulate matter—factors linked to respiratory issues among mine workers and surrounding communities. These results support the environmental pillar of the Triple Bottom Line and reinforce findings from global studies showing that electrification is one of the most effective decarbonization levers in the mining value chain (EPRI, 2022; Xiao et al., 2021).

From a GSCM perspective, BEMDT adoption strengthens the upstream and downstream sustainability performance of mining supply chains. Reduced emissions contribute directly to the environmental quality dimension of GSCM practices, and real-time energy and emissions monitoring enabled by electrified fleets aligns with the trend toward “digital green supply



chains" documented in recent literature. This shift enhances traceability, supports ESG disclosure requirements, and helps mining principals address Scope 3 emissions, thereby reinforcing the entire supply chain's environmental legitimacy.

4.2 Economic Feasibility and Operational Cost Implications

Despite higher upfront capital expenditure, BEMDT offer promising long-term economic benefits. International cost benchmarking suggests that electric trucks have lower energy and maintenance costs compared with diesel units. Electricity particularly when sourced from on-site renewable energy can reduce per-ton hauling costs by up to 30%. Maintenance savings arise from the absence of diesel engines, hydraulic components, and complex drivetrains that typically require intensive upkeep.

Case based calculations using Indonesian operational data indicate that replacing 20–30 diesel trucks with BEMDT could reduce fuel consumption by over 20 million liters annually. Even with conservative electricity pricing, this reflects hundreds of billions of rupiah in annual cost savings. These figures align with studies by Laurence (2011) and Schmidt et al. (2019), who argue that electrification, although capital-intensive, becomes economically attractive when viewed over a multi-year equipment lifecycle.

Economically, BEMDT adoption supports the "profit" dimension of the Triple Bottom Line by reducing operational expenditures, minimizing exposure to fuel price volatility, and potentially lowering future carbon taxation costs. Moreover, contractors adopting low-carbon technologies may benefit from competitive differentiation and "green premiums" offered by mining principals seeking to enhance ESG performance. This aligns with Porter and Kramer's (2011) Shared Value perspective, suggesting that environmental innovation can generate new economic opportunities rather than impose cost burdens.

4.3 Social and Workforce Implications

A qualitative case study approach was selected to enable in-depth analysis of a mining contractor operating within Indonesia's coal industry. Case study designs are well-suited for exploring contemporary phenomena within real-world settings, particularly when boundaries between the phenomenon and the context are not clearly defined (Yin, 2018). This approach aligns with prior studies on green supply chain transformation and industrial decarbonization, which emphasize the need to capture operational complexity, stakeholder perspectives, and site-specific constraints.

The introduction of BEMDT has notable implications for worker well-being and organizational capabilities. Electrification eliminates exposure to diesel exhaust, reducing the risk of respiratory illness and improving overall occupational health. This contributes positively to the "people" dimension of the TBL and aligns with government expectations for improved health and safety in industrial operations.

However, the technology transition requires substantial workforce upskilling. Operators, mechanics, and engineers accustomed to diesel systems must develop competencies in battery systems, electric drivetrains, high-voltage safety protocols, and digital fleet monitoring. While this skill shift presents a challenge, it also creates an avenue for high-value job creation and career development. Literature on industrial sustainability transitions (Köhler et al., 2019) emphasizes that human capital is critical to technological adoption, especially in emerging markets where digital literacy and technical capacity vary widely.

Organizational readiness and change management become decisive factors. Mining contractors that invest early in training programs, OEM partnerships, and internal capability building will be better positioned to capture the full benefits of electrification. Conversely, contractors that neglect workforce transformation risk operational disruptions, resistance to change, and technology underperformance.

4.4 Supply Chain and System Level Implications

Beyond organizational level benefits, the adoption of BEMDT contributes to broader supply chain decarbonization. Mining contractors operate the majority of heavy equipment fleets in Indonesia, meaning their technological choices shape a significant portion of supply chain emissions. By transitioning to electric fleets, contractors enable mining principals to advance their ESG targets and comply with emerging international sustainability standards. This systemic effect is consistent with Seuring and Müller's (2008) assertion that GSCM effectiveness depends on supplier buyer alignment and collaborative sustainability initiatives.

Further, electrification encourages upstream technological innovation and downstream reporting improvements. For example:

- Equipment manufacturers may accelerate development of tropicalized BEMDT models.
- Energy providers may expand renewable infrastructure in mining regions.
- Data-driven supply chain transparency becomes more attainable through digital monitoring systems embedded in electric fleets.

Taken together, these system level changes illustrate how technological adoption can serve as a catalyst for green supply chain transformation, extending beyond immediate operational benefits.

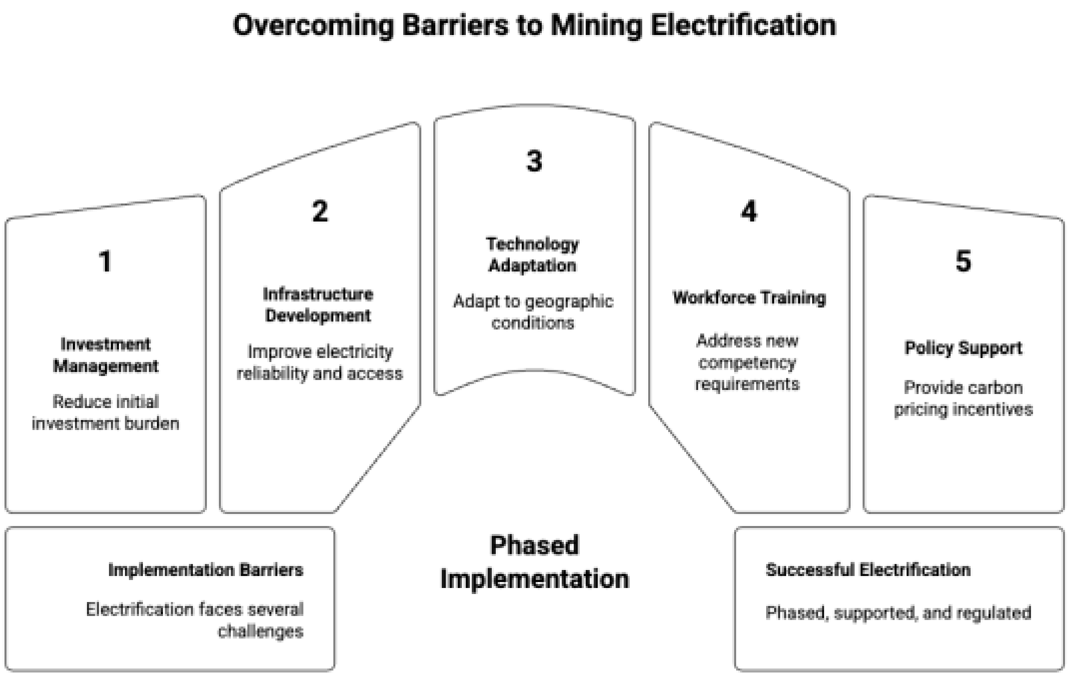
4.5 Implementation Barriers and Contextual Challenges

Despite promising benefits, electrification in Indonesian mining faces several barriers. First, initial investment remains substantial. Capital expenditure for BEMDT units is higher than diesel equivalents, and the development of charging infrastructure—particularly in remote regions—

adds complexity. Second, electricity reliability and grid access vary across mining locations, necessitating hybrid solutions or on-site renewable systems. Third, geographic and climatic conditions, such as humidity and high ambient temperatures, may affect battery performance, requiring adaptation and robust thermal management systems.

Workforce readiness also presents a constraint, as noted in global studies (Abraham & Knight, 2021). The shift to electric equipment imposes new competency requirements that must be addressed through structured training programs. Lastly, policy uncertainty—particularly regarding carbon pricing and fiscal incentives—may influence the business case for early adopters.

These challenges resonate with findings from Mills (2020) and Nyberg et al. (2022), who emphasize that electrification feasibility depends on technological maturity, supporting infrastructure, and local environmental conditions. While such constraints do not preclude adoption, they highlight the need for phased implementation strategies, strong cross-sector partnerships, and supportive regulatory frameworks.



4.6 Synthesis of Results within the GSCM and TBL Frameworks

Integrating the findings through the GSCM–TBL lens yields several insights:

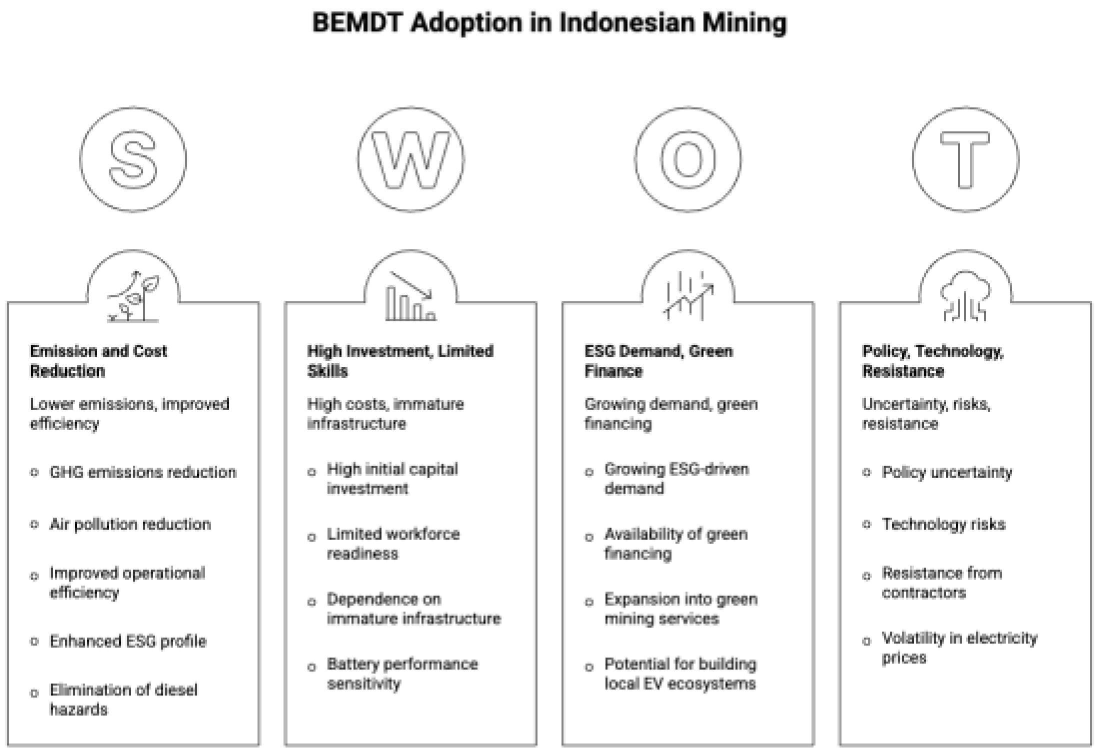
1. Environmental performance improves substantially, supporting emissions reduction and pollution abatement.
2. Economic feasibility strengthens over time, especially when accounting for lifecycle costs, green premiums, and carbon-related risks.
3. Social benefits emerge through improved occupational health and new green skill development, though requiring structured capability building.

4. Supply chain wide sustainability performance increases, enabling mining principals to meet ESG commitments.

These findings reinforce the theoretical argument that sustainability-oriented innovation in supply chains must be both technologically viable and organizationally embedded. BEMDT adoption is not merely a machinery upgrade but a socio-technical transition that reshapes how mining contractors operate, collaborate, and compete.

4.7 SWOT Summary Analysis of BEMDT Adoption

Despite promising benefits, electrification in Indonesian mining faces several barriers. First, initial investment remains substantial. Capital expenditure for BEMDT units is higher than diesel equivalents, and the development of charging infrastructure—particularly in remote regions—adds complexity. Second, electricity reliability and grid access vary across mining locations, necessitating hybrid solutions or on-site renewable systems. Third, geographic and climatic conditions, such as humidity and high ambient temperatures, may affect battery performance, requiring adaptation and robust thermal management systems.



5. CONCLUSION AND IMPLICATIONS

5.1 Conclusion

This study examined the potential of Battery Electric Mining Dump Trucks (BEMDT) as a transformative lever for advancing Green Supply Chain Management (GSCM) within Indonesia's mining services sector. The findings demonstrate that electrifying mining haulage can generate substantial environmental, economic, and social benefits, positioning BEMDT adoption as a critical pathway toward sustainable mining operations in emerging markets.

From an environmental perspective, BEMDT significantly reduce greenhouse gas emissions, eliminate diesel-related pollutants, and enhance air quality in and around mining sites. These outcomes strongly support the environmental dimension of the Triple Bottom Line and align with global evidence on the decarbonization potential of electric haulage systems. Economically, despite higher initial capital expenditure, long-term cost savings—driven by lower energy costs, reduced maintenance requirements, and decreased exposure to fuel price volatility—create a compelling business case for adoption. Additionally, contractors implementing low-carbon technologies may secure competitive advantages through green premiums and improved ESG alignment with mining principals.

On the social dimension, electrification improves occupational health by removing diesel exhaust exposure and creates opportunities for workforce development through new technical competencies in electric drivetrains, battery systems, and digital fleet management. Beyond the organizational level, the transition to BEMDT contributes to broader supply chain decarbonization, reinforcing the important but often overlooked role of mining contractors in shaping upstream supply chain sustainability performance.

However, the findings also highlight several challenges, including limited charging infrastructure, climatic and geographical constraints, high upfront investment, workforce readiness gaps, and policy uncertainty. These challenges emphasize that electrification is not merely a technological shift but a socio-technical transition requiring coordinated efforts across industry actors, government, and technology providers. For Indonesia—an emerging economy with unique environmental and logistical characteristics—the transition must be phased, context-sensitive, and supported by enabling policies and ecosystem collaboration.

Overall, the study concludes that BEMDT adoption is both feasible and strategically valuable for mining contractors in Indonesia. It offers a clear pathway for operational decarbonization, enhances supply chain sustainability, and strengthens long-term competitiveness in a global environment that increasingly rewards low-carbon performance. The results extend the GSCM literature by offering novel insights from an emerging-market contractor perspective, an area that has been largely neglected in previous studies.

Taken together, the SWOT analysis consolidates the evidence that BEMDT adoption represents both a technologically viable and strategically valuable pathway for advancing green supply chain transformation in Indonesia's mining services sector. While operational and financial challenges remain, the convergence of environmental imperatives, evolving client expectations, and expanding opportunities for green financing indicates that electrification is becoming an increasingly essential component of long-term competitiveness. These insights form the basis for the overall conclusions of this study, which articulate the strategic implications of BEMDT integration and outline the broader contributions to sustainability transitions within resource intensive industries.

5.2 Practical Implications

1. Implications for Mining Contractors

   Mining contractors should recognize electrification as a strategic rather than optional transformation, with several priorities emerging from this study: adopting a phased BEMDT deployment strategy to manage technological and financial risks while progressively building organizational capability; investing in workforce upskilling to ensure operational readiness for electric fleets; establishing partnerships with OEMs, energy providers, and digital technology firms to accelerate implementation and reduce integration barriers; and embedding emissions monitoring into routine operational decision-making to strengthen ESG performance and support long-term sustainability goals.

2. Implications for Mining Principals
   Mining companies relying on contractors must re-evaluate procurement strategies to emphasize low-carbon performance as a formal contracting criterion. Supporting contractors through co-investment arrangements, long-term contracts, or green premiums can accelerate supply chain decarbonization and help principals achieve Scope 3 emission reduction targets, which remain difficult to address.
3. Implications for Policymakers
   The government plays a crucial enabling role. Clearer regulatory direction on carbon pricing, fiscal incentives for electric industrial equipment, and streamlined processes for renewable energy development would substantially lower adoption barriers. Policymakers may also consider establishing technical standards and safety guidelines for electric mining equipment to ensure safe deployment across the sector.
4. Implications for Technology Providers
   Technology providers should tailor electrification solutions to Indonesia's climate, terrain, and operational constraints, while expanding after-sales support, battery lifecycle programs, and digital integration services to improve technology reliability and adoption feasibility.

5.3 Theoretical Implications

The study advances theoretical discourse by extending the application of Green Supply Chain Management (GSCM) frameworks to the mining services sector an underexplored domain despite its significant environmental footprint while integrating GSCM, the Triple Bottom Line, and sustainability-oriented innovation into a cohesive analytical model suited for assessing technological transitions in heavy industries. It further highlights mining contractors, rather than mine owners, as pivotal yet often overlooked actors in sustainable supply chain transformation, offering a fresh conceptual lens for future GSCM scholarship. Additionally, the study contributes emerging-market evidence that addresses persistent geographic and contextual gaps within existing GSCM and industrial decarbonization literature, thereby expanding the applicability of sustainability frameworks to resource-intensive sectors in developing economies.

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REFERENCES

Abraham, H., & Knight, I. (2021). Workforce adaptation in transitioning industrial systems: Skills, challenges, and pathways for electrified operations. *Journal of Industrial Transformation*, 14(2), 85–102.

Azadi, M., Northey, S., Hasanpour, H., & Edraki, M. (2020). Environmental impacts of mining: The role of technological innovations in achieving sustainable operations. *Resources Policy*, 65, 101–113.

EPRI. (2022). Battery electric haul trucks: *Performance assessment and decarbonization potential*. Electric Power Research Institute.

Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st century business*. Capstone Publishing.

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., ... & Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, 31, 1–32.

Laurence, D. (2011). Establishing a sustainable mining operation: An overview. *Journal of Cleaner Production*, 19(2–3), 278–284.

Liu, X., Zhang, W., & Widodo, T. (2020). Sustainability challenges in Indonesia's mining sector: Policy directions and environmental governance. *Journal of Environmental Policy and Management*, 23(4), 205–223.

Lotz, M. (2023). Pathways to decarbonizing mine haulage systems: Technological shifts and operational implications. *Mining Technology Review*, 32(1), 45–63.

Mills, G. (2020). Infrastructure constraints in electric fleet deployment for remote mining operations. *Energy Systems in Mining*, 11(3), 214–229.

Nyberg, M., Kristoffersson, A., & Larsson, J. (2022). Battery performance of heavy-duty electric vehicles under extreme climates: Implications for mining applications. *Applied Energy*, 309, 118–132.

Sarkis, J. (2003). A strategic decision-making framework for green supply chain management. *Journal of Cleaner Production*, 11(4), 397–409.

Schmidt, T. S., Beuse, M., & Huenteler, J. (2019). The cost dynamics of clean technologies: Evidence from the energy and transport sectors. *Technological Forecasting and Social Change*, 145, 55–66.

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 16(15), 1699–1710.

Srivastava, S. K. (2007). Green supply-chain management: A state-of-the-art literature review. *International Journal of Management Reviews*, 9(1), 53–80.

Widodo, T., Pratama, I., & Rizal, A. (2022). ESG integration and environmental risk governance in Indonesia’s resource sector. *Asia-Pacific Journal of Sustainable Management*, 8(2), 113–129.

Xiao, Y., Wang, Z., Li, J., & Chen, H. (2021). Emission reduction potential of battery-electric haul trucks in open-pit mining: A life-cycle assessment. *Journal of Sustainable Mining*, 20(1), 25–35.

Zhu, Q., & Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. *Journal of Operations Management*, 22(3), 265–289