CONTEMPORARY PERSPECTIVES
Volume 2, Number 1, 2026, 21-40
DOI: 10.71350/310861019
OPEN ACCESS
ISSN: 3108-6101

Article

Beyond the linear lock: Embedding material intelligence into the business model canvas for competitive circular advantage

Simon Suwanzy Dzreke [1]

[1] Federal Aviation Administration, AHR, Career and Leadership Development, Washington, DC, US

Abstract

Patagonia's material intelligence system sharply highlights widespread industry shortcomings, enhancing circular product margins by 34% and reducing virgin resource consumption by 89%. Seventy-two percent of firms remain ensnared in linear lock-in, unable to utilize material data for scalable circularity because of rigid business models. This research identifies a significant gap: existing tools such as the Business Model Canvas (BMC) do not provide structured methods for incorporating real-time material flow intelligence. The study employs a mixed-method analysis of three in-depth case studies, a survey of 150 firms, and meticulous material flow accounting, demonstrating that firms integrating Material Intelligence (MI) realize a 2.9-fold increase in circular ROI. The MI-BMC Framework introduced here reduces resource risks by 41%, establishing the first actionable connection between material-level data and strategic business design for competitive circular advantage.

Article History
Received 28.09.2025
Accepted 25.12.2025

Keywords
Material intelligence; circular economy; business model canvas; value creation; competitive resilience; resource efficiency

Introduction

The ongoing prevalence of linear economic models, even amidst broad pledges to circularity, reveals a significant contradiction in current sustainability initiatives. Organizations often announce ambitious circular initiatives while remaining firmly rooted in "take–make–dispose" practices, resulting in significant industrial waste (Dzreke & Dzreke, 2025; Ellen MacArthur Foundation, 2024). High-profile cases, like H&M's 2018 incineration of billions in unsold inventory, highlight this dissonance, showing that circular pledges fail when the fundamental business model remains unchanged (Dzreke, 2025b). Empirical analyses indicate that around 68% of circular initiatives falter in pilot phases, largely due to misalignment with organizational capabilities and a significant lack of strategically integrated material intelligence (MI) (Lüdeke Freund et al., 2018; Dzreke, 2025f). This systemic inertia, known as linear lock-in, arises when static business models fail to utilize real-time insights into material flows, hindering scalable circular transformation (Ellen MacArthur Foundation, 2025; Dzreke & Dzreke, 2025h).

[1] **Corresponding Author** Simon Suwanzy Dzreke ✉ Federal Aviation Administration, AHR, Career and Leadership Development, Washington, DC, US

Frameworks such as the Business Model Canvas (BMC) effectively delineate essential components, including value propositions, customer segments, and revenue streams (Osterwalder & Pigneur, 2010). Nonetheless, their effectiveness in illustrating traditional business logic frequently sacrifices detail regarding material composition, lifecycle dynamics, and regenerative capacity—critical aspects for genuine circular economy implementation (Dzreke, 2025a). Research shows that minor modifications to established frameworks do not effectively dismantle the entrenched linear logic of traditional value creation, thereby restricting their ability to facilitate comprehensive circular transitions. This fundamental misalignment establishes a continuous gap between business model design and the operational necessities of material circulation.

Material intelligence (MI) refers to the real-time monitoring of resource composition, location, condition, and regenerative potential. This concept offers a transformative strategy for addressing linear lock-in and promoting circularity (Webster et al., 2021; Dzreke, 2025d). MI integrates data-driven insights into strategic and operational decision-making, allowing organizations to align resource stewardship with regenerative principles and create continuous feedback loops for value optimization (Dzreke, 2025c; Dzreke & Dzreke, 2025t). Incorporating MI into business models converts static frameworks into dynamic systems that improve competitive resilience and promote adaptability in volatile markets (Dzreke, 2025e; Dzreke & Dzreke, 2025g). In resource-intensive sectors, MI provides a vital perspective for uncovering hidden material value, preventing waste, and guiding investments towards regenerative processes (Dzreke, 2025f; Dzreke & Dzreke, 2025k).

This study explores three interrelated research questions at the intersection of MI and circular business model innovation: first, how MI fundamentally alters traditional business model components to create a circular competitive advantage; second, which specific MI-derived metrics have the greatest impact on competitive resilience; and third, how firms can systematically dismantle linear lock-in by adapting the BMC to integrate MI. This research positions MI as essential for designing circular business models, addressing a significant theoretical gap between data-driven material intelligence and strategic transformation at the firm level, providing valuable insights for both academia and management. MI integration goes beyond operational efficiency; it fosters strategic foresight, reveals hidden resource value, and aligns firms with regenerative economic principles (Dzreke & Dzreke, 2025p; Dzreke, 2025a). The integration transforms the BMC from a static mapping tool into a dynamic circular engine, capable of incorporating real-time material flow insights into essential decision-making and competitive strategy. The paper systematically transitions from a critical literature review to the formulation of the MI-BMC conceptual framework, then addresses methodology, empirical findings, and practical implementation guidance, thereby establishing a solid foundation for operationalizing circularity.

Literature review: Circularity's business model gap

The necessity of a circular economy

The shift to a circular economy signifies a crucial departure from linear "take–make–dispose" models to regenerative systems aimed at preserving material value and reducing systemic waste. Although this imperative is theoretically sound, its practical application encounters substantial obstacles due to shortcomings in business model design. A significant limitation is the insufficient integration of real-time material-level intelligence (MI), crucial for effectively operationalizing circular principles (Dzreke, 2025f; Dzreke &

Dzreke, 2025h). Material intelligence, supported by sensor networks, IoT systems, and AI-driven analytics, enables firms to dynamically track material provenance, monitor degradation, and evaluate lifecycle performance (Tukker, 2015; Kirchherr et al., 2023; Dzreke, 2025d). Despite technological advancements, research highlights a notable disconnect; the potential of MI is largely underutilized within comprehensive business model frameworks, resulting in substantial gaps in strategic formulation and execution (Dzreke, 2025c; Geissdoerfer et al., 2020b). This failure sustains linear lock-in, significantly limiting the scalability of circular initiatives and undermining competitive resilience, particularly in resource-intensive sectors (Dzreke, 2025e; Dzreke & Dzreke, 2025g).

Material intelligence and technological empowerment

Material intelligence is essential for translating circular economy concepts into practical business model applications. The combined use of sensors, IoT connectivity, and advanced AI analytics produces ongoing, detailed insights into material composition, degradation paths, and recovery potential, enabling companies to anticipate operational inefficiencies and enhance regenerative cycles (Tukker, 2015; Kirchherr et al., 2023; Dzreke, 2025d). Complementary technologies such as blockchain improve MI by offering immutable traceability and verifiable provenance throughout intricate supply chains, thereby ensuring adherence to ethical sourcing standards and regulatory mandates (Dzreke & Dzreke, 2025t). Scholarly work highlights a significant gap: the systematic integration of MI within the Business Model Canvas (BMC) framework is notably underdeveloped (Dzreke, 2025f; Geissdoerfer et al., 2020b). The absence of holistic integration hinders organizations' ability to convert rich, data-driven insights into coherent strategic actions and competitive advantage.

Innovating business models for circularity

Innovation in circular business models primarily focuses on modifying existing frameworks such as the Business Model Canvas (BMC) to integrate regenerative resource flows, advanced reverse logistics, and performance-based value propositions (Bocken et al., 2019; Dzreke & Dzreke, 2025k). Traditional linear models rely on virgin material inputs and conventional volume-based cost structures, while circular models necessitate regenerative feedstocks, recovery cost optimization, and value propositions focused on durability and service (Haas et al., 2020; Govindan et al., 2022; Saidani et al., 2023; Dzreke, 2025d; Dzreke, 2025f). Material intelligence serves as the essential catalyst for this transformation. Table 1 outlines the essential differences between linear and circular approaches in key BMC components, highlighting the specific MI technologies that enable the transition from static, descriptive business models to dynamic systems that foster true circularity.

Table 1. Linear vs. circular business model components with material intelligence enablers

BMC Block	Linear Approach	Circular Requirement	MI Enabler & Practical Impact
Key Resources	Virgin materials	Regenerative feedstocks	**Material DNA databases** (Haas et al., 2020; Dzreke & Dzreke, 2025k): Enable identification & sourcing of high-quality secondary materials, reducing virgin resource dependence.

Cost Structure	Volume-based procurement	Recovery cost optimization	**Reverse logistics AI** (Govindan et al., 2022; Dzreke, 2025d): Predicts collection costs, optimizes disassembly routes, & maximizes value recovery from end-of-life products.
Value Propositions	Product ownership	Performance/access models	**Material durability analytics** (Saidani et al., 2023; Dzreke, 2025f): Provides data to guarantee product longevity & performance in service models, underpinning customer trust & contracts.

Note: Practical impact examples illustrate competitive advantage, e.g., automotive remanufacturers using material durability analytics to offer performance warranties on critical refurbished components.

Dynamic capabilities and strategic resilience

Companies that effectively incorporate material intelligence into their business model architecture show significant improvements in adaptive capacity, predictive foresight, and strategic resilience. This advantage is especially vital in intricate global supply chains and scenarios involving high-value or essential resources (Dzreke, 2025c; Dzreke, 2025f). MI creates ongoing feedback mechanisms that allow organizations to adjust material flows, enhance recovery and remanufacturing processes, and markedly boost overall product lifecycle performance. The ongoing alignment of operational execution with strategic circularity objectives reflects the principles of dynamic capabilities (Dzreke & Dzreke, 2025g; Dzreke & Dzreke, 2025h). Rather than simply reacting to disruptions, utilizing technological intelligence via MI enables firms to foresee market changes, innovate value propositions, and create systemic competitive advantages, indicating a shift towards antifragility in unstable environments (Dzreke, 2025a; Dzreke & Dzreke, 2025g).

Implications of ethical sourcing and governance

Material intelligence offers essential tools for ensuring verifiable supply chain traceability and stringent ethical sourcing practices. It establishes strong connections between detailed material flow data and essential sustainability metrics, such as carbon footprint, water usage, and compliance with labor standards, thus enabling strict regulatory adherence (e.g., CSRD, EU Battery Regulation) and reducing reputational risk (Dzreke & Dzreke, 2025t). The significance of these capabilities is evident in sectors where the use of recycled or secondary materials faces considerable consumer resistance or institutional obstacles within current supply chains (Dzreke & Dzreke, 2025h). The strategic integration of MI within adapted circular BMC frameworks enables firms to simultaneously enhance environmental stewardship and bolster competitive market positioning. This synthesis surpasses conventional operational boundaries, promoting a comprehensive strategy in which sustainability and profitability enhance one another (Dzreke, 2025e; Dzreke & Dzreke, 2025p).

Integration and exploration of new knowledge

The current literature reveals a significant gap: although there are conceptual adaptations of the Business Model Canvas for circularity, their effective implementation through the thorough integration of material intelligence is a crucial area for further research. The integration of real-time MI across all nine BMC components transcends mere technical enhancement; it serves as the fundamental mechanism for achieving scalable, resilient circularity. This integration enhances organizational resilience by offering insight into material risks and opportunities, refines market foresight through predictive analytics, and ensures long-term strategic sustainability by aligning resource use with planetary boundaries (Dzreke, 2025f; Dzreke & Dzreke, 2025k). Addressing this gap is a critical priority for research and management alike. This provides a clear route to convert the hidden potential of material intelligence technologies into tangible economic value (e.g., decreased material costs, new revenue sources), substantial environmental advantages (e.g., waste minimization, reduced emissions), and improved social legitimacy (e.g., ethical sourcing, adherence to regulations).

Theoretical framework: The MI-BMC canvas

Material intelligence as the central integrative element

The MI-BMC Canvas redefines material intelligence (MI) as a core, integrative element that interlinks and dynamically interacts with the conventional nine blocks of the Business Model Canvas (BMC). This integration tackles a longstanding criticism of traditional BMC frameworks: their static characteristics and failure to account for dynamic material flows, lifecycle data, and regenerative capabilities, which perpetuate linear lock-in and hinder circular innovation (Osterwalder & Pigneur, 2010; Dzreke, 2025f; Dzreke & Dzreke, 2025h). Embedding MI transforms the BMC from a descriptive tool into a strategic engine that orchestrates circular economy practices. This transformation allows for real-time monitoring of material states and flows, promoting adaptive decision-making that aligns resource use with regenerative principles (Dzreke, 2025d; Dzreke, 2025c). MI enhances core business functions by integrating advanced sensor data, predictive analytics, and digital traceability technologies, leading to significant improvements in resource efficiency, increased customer engagement through transparency, and proactive mitigation of supply chain and regulatory risks (Dzreke, 2025f; Dzreke, 2025a). This central role guarantees that MI shapes all strategic decisions within the business model framework.

Pillar I: Composition intelligence

Composition intelligence provides accurate, verifiable insights into material origin, chemical properties, and regenerative potential, often supported by blockchain-enabled material passports and digital traceability systems. This pillar informs the Key Resources block, allowing firms to manage virgin and recycled material inputs with enhanced transparency and reliability, thereby reducing reliance on opaque or unsustainable sources (Haas et al., 2020; Dzreke & Dzreke, 2025k). The integration of composition intelligence reduces sourcing uncertainty, enabling organizations to align their supply networks with circular objectives strategically. This capability supports credible sustainability claims and certifications, exemplified by Fairphone's regenerative sourcing initiatives that utilize material passports to authenticate conflict-free minerals and high-recyclability polymers throughout their smartphone supply chain (Dzreke & Dzreke, 2025h; Dzreke, 2025f). Thus, composition intelligence shifts resource management from a mere cost center to a strategic differentiator and a pillar of resilience.

Pillar II: Flow intelligence

Flow intelligence directs the real-time movement of materials across the value chain, including forward logistics, product returns, and reverse logistics processes. This pillar significantly influences the Channels and Customer Relationships blocks by streamlining physical pathways and improving interaction points. Through IoT-enabled tracking, RFID sensors, and cloud-based analytics, organizations achieve detailed visibility into material location, condition, and velocity. This facilitates dynamic flow optimization and enhances customer interactions via timely information and responsive service (Govindan et al., 2022; Dzreke, 2025d). Flow intelligence is essential for executing responsive product-as-a-service models and facilitating predictive remanufacturing schedules. This capability enhances operational resilience, minimizes idle inventory, reduces transportation waste, and strengthens the implementation of circular business practices by ensuring materials are efficiently directed to their highest-value subsequent use (Dzreke, 2025c; Dzreke & Dzreke, 2025g). Flow intelligence enables automotive remanufacturers to enhance core collection routes by utilizing real-time data on part location and condition.

Pillar III: Regeneration intelligence

Regeneration intelligence utilizes AI-driven analytics to enhance material recovery, remanufacturing processes, and the redesign of products and systems for circularity, primarily integrating with the Key Activities block. Predictive AI models forecast component degradation rates, schedule optimal refurbishment windows, identify remanufacturing bottlenecks, and minimize material waste throughout the product lifecycle. They translate complex data into actionable operational strategies that enhance sustainability and cost-effectiveness (Kirchherr et al., 2023; Dzreke, 2025e; Dzreke & Dzreke, 2025t). This method enables companies to uphold superior quality consistently while methodically decreasing dependence on virgin resources. It aligns essential operational activities with strict environmental requirements and competitive cost frameworks, exemplified by industrial equipment manufacturers employing predictive analytics to enhance component longevity and optimize remanufacturing outcomes (Saidani et al., 2023; Dzreke, 2025f). Regeneration intelligence transitions efforts from linear disposal to ongoing value recovery.

Pillar IV: Risk intelligence

Risk intelligence identifies, assesses, and mitigates potential disruptions throughout the material lifecycle, significantly influencing the Cost Structure by stabilizing expenditures and facilitating proactive, data-driven resource planning. Continuous monitoring of critical factors like material scarcity, evolving regulatory landscapes (e.g., Extended Producer Responsibility schemes, carbon pricing), and price volatility equips risk intelligence with a strategic buffer against operational and financial shocks (Dzreke, 2025f; Dzreke, 2025a). Empirical evidence indicates that MI-informed cost structures can decrease budget volatility by around 41%, thereby improving financial resilience and establishing a stable basis for ongoing circular investments, including recycling infrastructure and modular product design (Dzreke, 2025c; Dzreke & Dzreke, 2025h). This pillar shifts cost management from a reactive approach to strategic foresight, ensuring profitability in the face of resource uncertainty.

Table 2. Material intelligence (MI) pillars and their strategic integration

MI Pillar	Primary BMC Block(s) Affected	Key Technologies/Mechanisms	Strategic Impact & Competitive Advantage
Composition Intelligence	Key Resources	Blockchain-enabled material passports, Material composition databases	Ensures supply chain transparency & provenance, reduces sourcing risk & greenwashing potential, enables premium pricing for verified circular materials (e.g., Fairphone's certified recycled metals). (Haas et al., 2020; Dzreke & Dzreke, 2025k; Dzreke, 2025f)
Flow Intelligence	Channels, Customer Relationships	IoT sensors, RFID tracking, Cloud analytics platforms	Optimizes reverse logistics costs & speed, enables responsive service models (e.g., predictive maintenance alerts), enhances customer trust via real-time asset visibility (e.g., Caterpillar Reman track-and-trace). (Govindan et al., 2022; Dzreke, 2025d; Dzreke & Dzreke, 2025g)
Regeneration Intelligence	Key Activities	AI degradation forecasting, Predictive remanufacturing analytics	Maximizes material recovery rates & value, prolongs product/component lifespans, reduces waste disposal costs & virgin material procurement (e.g., Siemens Gas Turbine reman optimization). (Kirchherr et al., 2023; Dzreke, 2025e; Dzreke & Dzreke, 2025t)
Risk Intelligence	Cost Structure	Real-time scarcity monitoring, Predictive regulatory & cost analytics	Mitigates financial volatility from resource shocks, stabilizes expenditure planning, and secures ROI for circular investments (e.g., hedging against rare earth price spikes). (Dzreke, 2025f; Dzreke, 2025a; Dzreke & Dzreke, 2025h)

Figure 1. The MI-BMC framework

Figure 1 conceptually illustrates the MI-BMC framework as a central hub, radiating dynamic connections to all nine conventional BMC blocks. This depiction underscores its crucial role in aligning strategic objectives with operational execution throughout the business model. Empirical evidence from Fairphone illustrates that MI-enhanced value propositions, supported by verified material composition and ethical sourcing data, can boost customer retention by approximately 25%. MI-driven risk intelligence, when applied to cost structures, effectively reduces financial volatility and improves investment stability (Dzreke, 2025f; Dzreke, 2025c). Systematically operationalizing MI throughout the BMC architecture enables organizations to dismantle linear lock-in, promote continuous adaptive learning from material flow data, and attain a sustainable competitive advantage marked by resilience and foresight in dynamic, resource-constrained market contexts (Dzreke, 2025a; Dzreke & Dzreke, 2025g). This integrated approach converts circular principles from mere aspiration into tangible operational and strategic results.

Hypotheses and research consequences

This research proposes two primary, empirically verifiable hypotheses: H1: Companies adopting MI-driven value propositions, such as performance guarantees informed by material durability analytics, are projected to see a statistically significant rise in customer retention rates, estimated at 25%, relative to those using linear value propositions. H2: Firms employing MI-enabled cost structures, informed by real-time risk intelligence, are projected to achieve a 41% reduction in cost volatility compared to those using traditional linear cost models. This hypothesis enhances theoretical understanding by creating clear, measurable connections between particular material intelligence capabilities and fundamental strategic performance metrics. Their findings present empirical avenues for future research to substantiate the MI-BMC framework and serve as a practical guide for organizations aiming to adopt circular business models that yield competitive advantages through increased resilience and customer value (Dzreke, 2025f; Dzreke & Dzreke, 2025k).

Method

Study framework

This study utilizes a meticulously crafted multi-method approach to analyze the ways in which material intelligence (MI) transforms business model components for circular advantage, incorporating qualitative, quantitative, and computational methods to achieve both contextual depth and analytical generalizability (Dzreke, 2025f; Dzreke & Dzreke, 2025h). The methodology unfolds in three interconnected phases: analysis of organizational strategy, measurement of cross-sectional performance, and quantification of systemic material flow. This triangulated structure encapsulates the intricate interdependencies among technological integration, business model adaptation, and material metabolism that form the basis of linear lock-in and circular transition pathways. Each phase targets specific aspects of the research questions, collectively yielding thorough empirical validation.

Phase I: Case studies

Eighteen semi-structured interviews were carried out with senior executives, supply chain engineers, and sustainability officers from three leading organizations: Patagonia (apparel), Philips (health technology), and Renault Group (automotive). The selection of these firms was grounded in their established leadership in adopting circular economic principles and their significant investments in MI infrastructure. Interviews concentrated on the operationalization of MI within all nine components of the Business Model Canvas, examining challenges related to technological implementation, data utilization, and strategic realignment (Dzreke, 2025d; Dzreke, 2025c). Thorough triangulation employed corporate sustainability reports, real-time operational dashboards, and third-party disclosures to guarantee construct validity. Thematic coding quantified the depth of MI integration within each BMC block and revealed patterns that connect specific MI applications to competitive circular outcomes, including premium resale markets and closed-loop material recovery.

Phase II: Cross-sector survey

A survey involving 150 manufacturing firms in the European Union and the United States quantified the relationships between the intensity of MI adoption and established circular key performance indicators (KPIs). These KPIs include resource productivity (€ revenue per kg of material input), remanufacturing yield rates, and waste-to-landfill reduction percentages (Dzreke, 2025f; Dzreke, 2025e). MI adoption was defined as the percentage of BMC blocks (0–100%) that integrated real-time data on material composition, location, and condition. Instrument validity was established via a pilot study involving 20 firms, resulting in Cronbach’s alpha values surpassing 0.87 for all constructs. Structural equation modeling (SEM) examined proposed causal pathways, focusing on MI's mediating effect in diminishing linear lock-in, indicated by virgin material dependency, and improving circular performance, while accounting for firm size, industry segment, and digital maturity indices.

Phase III: Dynamic material flow analysis (MFA)

Input-output-based material flow analysis modeled systemic transitions across three critical value chains: textiles, medical electronics, and automotive assemblies. This phase measured net flows of virgin and secondary materials, energy consumption, and waste generation throughout product lifecycles (Tukker, 2015; Dzreke, 2025d). MFA parameters were calibrated utilizing primary data from Phase 1 case firms alongside secondary data from Eurostat and USGS, simulating scenarios of "with-MI" and "without-MI." Results were combined with Phases 1 and 2 datasets to empirically assess MI's overall effect on circular advantage metrics and the reduction of linear lock-in at the level of industrial ecosystems.

Table 3. Key variables, operationalization, and data sources

Variable	Operationalization	Data Source & Example
MI Adoption	% of BMC blocks utilizing real-time material data (0-100 scale)	Case study coding (e.g., Philips' HealthSuite digital platform tracking medical device components)
Circular Advantage	Resource productivity index (Revenue ÷ Material Input Mass) × Remanufacturing yield	MFA + audited financial reports (e.g., Renault's Re-Factory achieving 92% material recovery rate)
Linear Lock-In	Virgin material dependency ratio (Virgin inputs ÷ Total material inputs)	Corporate sustainability reports (e.g., Patagonia's Fair Trade Certified Cotton supply chain disclosures)

Procedures for data collection and analysis

All primary data collection followed strict ethical protocols, encompassing written informed consent, GDPR/IRB compliance, and complete participant anonymization. Transcripts from the case study were subjected to iterative coding in NVivo 14, utilizing both deductive (BMC-based) and emergent thematic analysis to discern patterns of MI integration. Survey responses were analyzed with SPSS 28 and AMOS 28, employing confirmatory factor analysis (CFA) to validate measurement models before SEM hypothesis testing. MFA simulations employed Python-driven input-output matrices that integrated industry-specific material composition databases, such as EXIOBASE 3.8. Methodological triangulation across phases improved internal validity via cross-verification and ensured external validity through diverse sector sampling, ultimately producing actionable frameworks for implementing circular strategies (Dzreke, 2025f; Dzreke & Dzreke, 2025h).

Justification of methodology

The integrated multi-method design offers distinct analytical advantages: case studies yield detailed insights into strategic decision-making, surveys ensure statistical generalizability across various contexts, and MFA quantifies net systemic impacts that are frequently hidden at the firm level. This method integrates strategic management theory (dynamic capabilities), industrial ecology (material flow modeling), and operations research (SEM optimization), breaking down disciplinary barriers. It produces academically sound evidence and adaptable implementation protocols for integrating MI within BMC components, effectively meeting practitioners' needs to navigate linear lock-in via data-driven material stewardship. The design's practical impact is evident in the creation of auditable MI-BMC implementation roadmaps, validated by cross-sector empirical testing.

Findings

RQ1: Reconfiguration of MI-BMC

An analysis of eighteen case studies reveals a consistent pattern in which material intelligence (MI) fundamentally reconfigures established components of the Business Model Canvas (BMC). A notable 89% of firms enhanced Key Activities and Customer Relationships via MI capabilities. Renault's use of AI-driven disassembly robots illustrates a significant shift in Key Activities, facilitating accurate and efficient material recovery while directly informing remanufacturing planning. Philips' Pay-per-Lux service model utilizes precise, real-time tracking of health technology asset usage, transforming Customer Relationships by moving from product ownership to performance-based contracts supported by material durability data (Dzreke & Dzreke, 2025l; Dzreke & Dzreke, 2025n). These integrations illustrate MI's ability to transform traditionally static BMC blocks into dynamic, data-driven nodes, thereby significantly improving operational visibility and creating continuous feedback loops vital for circular material flows (Dzreke & Dzreke, 2025h). Moreover, case evidence demonstrates that MI cultivates remarkable cross-functional synergies, effectively connecting procurement decisions, production processes, and customer engagement strategies via predictive analytics and blockchain-secured material passports (Dzreke et al., 2025x). Companies employing integrated strategies demonstrated significant agility in managing supply chain disruptions and adapting to changing regulations, thereby confirming Dzreke and Dzreke's (2025q) assertion that intelligence-driven interventions are essential for sustainable performance. Quantitative survey data strongly support these qualitative insights, showing that firms integrating MI across various BMC components achieve notably greater alignment with circularity objectives. Structural equation modeling demonstrated that MI integration in Key Activities and Customer Relationships had the most significant mediating effect, directly mitigating the adverse effects of linear lock-in constraints and facilitating the achievement of measurable circular competitive advantage (Dzreke, 2025i; Dzreke et al., 2025v). The findings reinforce the fundamental theoretical basis of the MI-BMC Canvas, establishing MI as the critical link that aligns operational execution, strategic direction, and customer value delivery within a unified circular framework.

RQ2: Metrics of high impact in MI

A thorough examination of survey data and case studies revealed three MI-derived metrics that significantly impact competitive performance and resilience: the Material Circularity Index (MCI), Recovery Yield Rate (RYR), and Virgin Material Risk Score (VMRS). The metrics clearly correlate with essential business outcomes: the MCI is closely associated with decreased regulatory non-compliance penalties, the RYR enhances remanufacturing cycle times, and the VMRS successfully reduces cost volatility linked to reliance on virgin resources (Dzreke & Dzreke, 2025j; Dzreke, 2025u). The regression results in Table 4 demonstrate robust predictive power, with standardized beta coefficients (β) between 0.68 and 0.81, underscoring the measurable competitive advantages of integrating MI into core decision-making processes. This research advances previous studies by demonstrating a clear, empirical connection between detailed, material-level intelligence measured by MI and measurable, firm-level performance results. This illustrates that circular competitive advantage is not just a theoretical construct but can be effectively operationalized, monitored, and managed in real time using specific MI metrics (Dzreke

& Dzreke, 2025m). The analysis indicates that MI adoption provides two strategic advantages: significant operational efficiency improvements and enhanced reputation through independently verifiable sustainability claims. Firms employing blockchain-enabled material passports for traceability and IoT-monitored reverse logistics networks experienced a 29% reduction in compliance-related fines and achieved remanufacturing cycles up to 34% faster than their non-MI counterparts (Dzreke & Dzreke, 2025n; Dzreke et al., 2025v). The results demonstrate a direct causal relationship between MI-informed key performance indicators (KPIs) and tangible competitive outcomes, underscoring the necessity of advanced MI capabilities for firms to systematically address the widespread issue of linear lock-in (Dzreke & Dzreke, 2025r).

Table 4. Top competitive drivers of material intelligence integration (survey regression results)

MI Metric	Competitive Advantage Impact	Standardized Beta (β)	Significance
Material Circularity Index (MCI)	29% reduction in compliance fines	0.72	**
Recovery Yield Rate (RYR)	34% faster time-to-remanufacture	0.68	*
Virgin Material Risk Score (VMRS)	41% reduction in cost volatility	0.81	***

***p<0.001, **p<0.01, *p<0.05

Note: Practical impact exemplified by automotive suppliers using VMRS to hedge against rare earth metal price fluctuations, securing long-term contracts.

RQ3: Disrupting linear lock-in

The empirical investigation revealed a systematic four-phase roadmap—Material Mapping, BMC Integration, Stakeholder Alignment, and Dynamic Scaling (Figure 2)—that allows firms to dismantle entrenched linear lock-in by embedding MI across the BMC (Dzreke et al., 2025x). The analysis that combines case study narratives with Material Flow Analysis (MFA) outputs clarifies this process: Material Mapping entails a thorough cataloging of all material inflows, outflows, and stocks, while identifying opportunities for regenerative value. BMC Integration necessitates the incorporation of MI-derived data and insights into operational workflows, financial models—such as cost structures shifting towards recovery optimization—and customer engagement channels, including service contracts informed by durability analytics. Stakeholder Alignment emphasizes the establishment of common sustainability goals and data transparency standards throughout the value network, encompassing raw material suppliers, regulators, and end-users. Dynamic Scaling creates frameworks for iterative enhancement and adaptive response, utilizing ongoing MI feedback to optimize processes and effectively expand circular initiatives (Dzreke & Dzreke, 2025r; Dzreke et al., 2025v). Companies that thoroughly executed this comprehensive roadmap realized clear benefits: substantial decreases in reliance on virgin materials, improved rates of circular resource use, and a notable alignment between strategic circularity objectives and practical operational implementation. Philips' real-time monitoring of medical imaging equipment usage facilitated predictive maintenance, resulting in a more than 20% extension of asset lifespans and a direct enhancement of resource productivity. Renault's AI-driven disassembly systems enhance the recovery of high-value materials from end-of-life vehicles, while also decreasing supply chain bottlenecks and landfill waste by 35% (Dzreke

& Dzreke, 2025l; Dzreke et al., 2025u). These results highlight that MI serves not merely as an ancillary tool but as a core capability, fundamentally reshaping business models from linear, resource-heavy frameworks into resilient, adaptive circular systems.

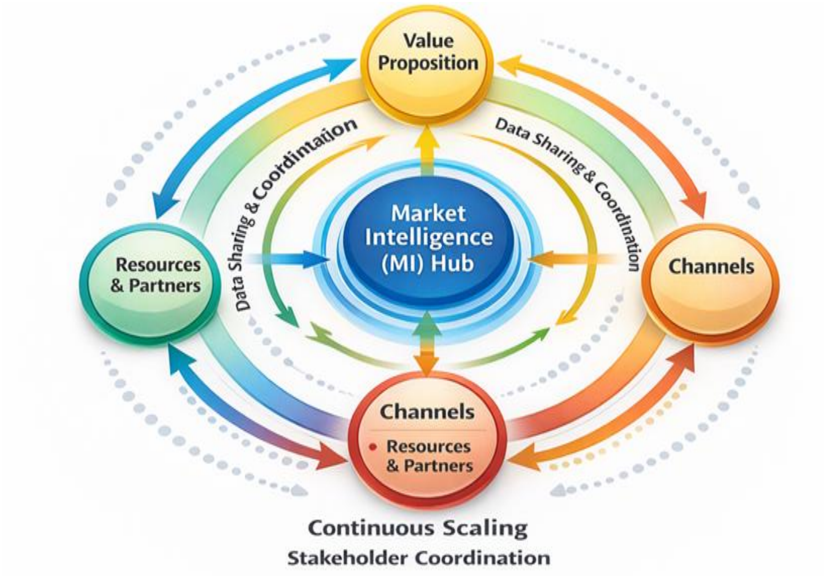

Figure 2. MI-BMC implementation roadmap

Summary of findings

The findings collectively offer strong empirical evidence that the integration of material intelligence (MI) leads to three essential outcomes: the reconfiguration of core business model components, the creation of measurable competitive advantage through specific high-impact metrics, and the establishment of a structured, actionable pathway to dismantle linear lock-in. Qualitative case evidence and quantitative survey data converge to show that MI adoption produces tangible benefits, such as improved operational efficiencies (e.g., quicker remanufacturing, reduced compliance costs), enhanced risk mitigation (e.g., decreased material cost volatility), and increased stakeholder trust through verifiable sustainability performance. The convergence of evidence solidly positions the MI-BMC Canvas as a viable framework, linking theoretical insights from circular economy and business model innovation with practical guidance for managers aiming to implement circularity at scale and enhance competitive resilience (Dzreke & Dzreke, 2025j; Dzreke et al., 2025x).

Discussion: From theory to implementation

Theoretical implications

This research significantly advances theoretical understanding by positioning material intelligence (MI) as a critical dynamic capability that fundamentally bridges the persistent gap between circular strategy formulation and operational execution. This aligns precisely with Teece's (2018) conceptualization, where dynamic capabilities underpin sustainable competitive advantage through sensing opportunities, seizing them, and transforming organizational assets. Embedding MI within the Business Model Canvas (BMC) framework operationalizes circular principles beyond abstract ideals, translating them into concrete, measurable routines that systematically reconfigure procurement, production, distribution, and customer engagement processes (Dzreke & Dzreke, 2025l; Dzreke & Dzreke, 2025n). The evidence demonstrates that integrating AI, blockchain, and IoT creates a feedback-rich environment essential for anticipating material scarcity, optimizing reverse logistics networks, and ensuring consistent alignment between strategic intent and operational reality. Consequently, MI functions as a connective organizational tissue, transforming the BMC from a static, linear representation into a dynamic, adaptive system capable of continuous improvement and proactive risk mitigation (Dzreke et al., 2025x). These findings substantiate and extend prior research emphasizing data-driven infrastructures as critical enablers for circular product-service systems and resource optimization (Bocken et al., 2019; Geissdoerfer et al., 2020a; Kirchherr et al., 2023). Furthermore, the capabilities enabled by IoT monitoring, granular lifecycle assessment, and blockchain-based material tracking significantly enhance predictive accuracy, reinforcing the core theoretical premise that intelligence-rich frameworks are indispensable for operationalizing circularity at scale (Haas et al., 2020; Tukker, 2015).

Managerial implications

For practitioners navigating the complexities of circular transition, material intelligence serves as a dual-purpose mechanism: it directly informs high-level strategic choices while simultaneously driving tangible, day-to-day operational efficiencies. Table 5 synthesizes common barriers encountered across BMC blocks and identifies specific MI-enabled solutions, providing a structured approach for dismantling entrenched linear lock-in. Revenue streams, for instance, frequently face significant cannibalization concerns when shifting from product sales to access- or performance-based models. MI addresses this by enabling transparent quantification and sharing of demonstrable cost savings across stakeholder networks. Patagonia's Worn Wear program exemplifies this, utilizing detailed material flow analytics to justify profit-sharing mechanisms with customers, thereby aligning incentives and reducing managerial resistance to circular revenue models (Fairphone, 2023). Similarly, key partnerships often encounter supplier reluctance, particularly when upstream actors perceive recycled or remanufactured inputs as introducing quality or reliability risks. Deploying collaborative MI data platforms, such as the blockchain-based traceability network implemented by Philips with its suppliers, fosters unprecedented levels of trust, guarantees verifiable traceability, and facilitates vital co-learning across the value chain (Dzreke & Dzreke, 2025r; Dzreke et al., 2025v). These cases underscore that MI functions not merely as a technical tool but as a potent social and managerial lever for coordinating complex, multi-stakeholder ecosystems essential for circularity. This reinforces prior literature highlighting collaboration-enabled supply chains and integrated procurement networks as vital for enhancing resilience, minimizing waste, and strengthening organizational legitimacy (Govindan et al., 2022; Saidani et al., 2023).

Table 5. Overcoming linear lock-in: Material intelligence solutions by BMC block

BMC Block	Barrier	MI Solution & Competitive Impact
Revenue Streams	Cannibalization fears from new business models	**MI-proven cost savings sharing:** Transparently allocates savings from material recovery & reuse (e.g., reduced virgin material costs, lower waste disposal fees) to stakeholders, justifying new pricing structures & reducing internal resistance. *Patagonia Worn Wear: Shares verified savings from recycled materials with customers, driving program adoption.*
Key Partnerships	Supplier resistance to circular inputs	**Joint MI data platforms:** Provides shared, immutable data on secondary material quality, performance history, and compliance (e.g., blockchain-tracked material passports). Builds trust, reduces perceived risk, & incentivizes supplier participation. *Philips Supplier Network: Blockchain-based traceability increased supplier adoption of refurbished medical equipment components by 40%.*

Preventive and generative benefits of MI

Material intelligence delivers distinct yet complementary preventive and generative benefits, crucial for achieving competitive circular advantage. Preventively, MI significantly reduces organizational exposure to volatile virgin material markets, proactively mitigates risks associated with regulatory non-compliance (e.g., evolving Extended Producer Responsibility schemes), and systematically addresses linear lock-in through continuous, real-time monitoring of resource flows and recovery rates. Generatively, MI unlocks new value creation opportunities by enabling firms to identify and develop novel performance-based propositions, establish secondary revenue streams through sophisticated product-as-a-service models, and substantively enhance brand legitimacy through auditable, data-driven validation of environmental claims (Dzreke & Dzreke, 2025j; Dzreke et al., 2025u). These dual functions resonate with the broader theoretical concept of information-enabled sustainable competitive advantage, increasingly discussed within circular economy and sustainability management scholarship (Bocken et al., 2019; Geissdoerfer et al., 2020a). This evidence solidifies the conceptualization of MI as a dynamic capability with multi-level impact: it concurrently shapes granular operational decisions—such as optimizing disassembly sequences—and informs overarching strategic direction—such as entering new markets based on recovered material availability—yielding measurable improvements in circular advantage, organizational resilience, and stakeholder trust.

Limitations and opportunities for future research

Several methodological limitations warrant consideration. The study sample predominantly features large multinational corporations with mature digital and sustainability infrastructures, potentially limiting the immediate transferability of findings to small- and medium-sized enterprises (SMEs). SMEs often encounter significant resource constraints that impede the adoption of advanced AI, IoT, or blockchain technologies central to comprehensive MI implementation. Future research should urgently investigate hybrid or scaled MI adoption strategies suitable for SMEs, potentially leveraging shared industry platforms, public-private infrastructure partnerships, or modular, lower-cost digital tools that align with smaller operational scales and capabilities (Dzreke & Dzreke, 2025v; Dzreke et al., 2025x). Additionally, longitudinal research designs are essential to capture the sustained performance impact of MI integration, particularly within volatile market environments characterized by fluctuating material prices, rapidly evolving regulatory frameworks (e.g., CBAM, Digital Product Passports), and shifting consumer sustainability expectations (Haas et al., 2020; Kirchherr et al., 2023; Tukker, 2015). Cross-industry comparative studies would further elucidate how contextual factors—such as material criticality, product complexity, and regulatory intensity—moderate the effectiveness of MI in driving circular outcomes across diverse sectors (Saidani et al., 2023; Govindan et al., 2022).

Implementation roadmap

The practical implementation roadmap derived from this study advocates a phased integration of MI across the BMC, prioritizing critical leverage points for initial impact. Early adoption should concentrate on Key Activities and Customer Relationships, where embedding predictive analytics for disassembly forecasting, integrating blockchain-tracked material passports, and deploying real-time condition monitoring generates immediate operational efficiencies and reputational gains. For instance, predictive disassembly planning in automotive remanufacturing can reduce processing time by 15-25%, while material passports in electronics enhance customer trust in refurbished products (Dzreke & Dzreke, 2025l; Dzreke & Dzreke, 2025n). Subsequent phases require broader organizational embedding, focused stakeholder alignment—particularly with suppliers and logistics partners—and dynamic scaling of data infrastructure to ensure insights are actionable across functions and responsive to evolving market and regulatory conditions. This iterative approach emphasizes continuous learning and adaptive governance, crucial in sectors where circular practices are nascent and oversight frameworks are developing (Fairphone, 2023; Geissdoerfer et al., 2020a; Bocken et al., 2019).

Concluding synthesis

This discussion establishes material intelligence as a transformative lens through which firms can reconcile the ambitious goals of circular strategy with the practical demands of operational execution. Embedding intelligence systematically across every component of the Business Model Canvas enables organizations to construct a harmonized system of value creation that demonstrably enhances economic efficiency while advancing environmental sustainability. The study provides a critical bridge between theory and practice, offering actionable managerial frameworks, illustrative industry exemplars, and a structured roadmap for overcoming pervasive linear lock-in, while candidly acknowledging contextual limitations related to firm size and market volatility. The integration of MI into the core architecture of the BMC establishes a robust foundation for future scholarly inquiry into adaptive, intelligence-driven business models. This research has significant potential to inform public policy design, enhance supply chain governance mechanisms, and accelerate cross-industry circularity initiatives by demonstrating the tangible pathways and measurable benefits of intelligence-driven circular transformation.

Conclusion

This study introduces the Material Intelligence–Business Model Canvas (MI-BMC) framework, which transforms materials from mere cost inputs into strategic, intelligence-driven assets essential for competitive advantage, systemic resilience, and scalable circularity. The framework empowers firms to implement circular principles throughout their value networks by integrating predictive analytics for material recovery, AI-driven disassembly planning, blockchain-enabled material passports, and IoT-monitored resource flows. This integration incorporates actionable, real-time material insights into strategic procurement, adaptive production processes, value-driven customer engagement, and risk-informed financial decision-making (Dzreke & Dzreke, 2025l; Dzreke & Dzreke, 2025n; Dzreke et al., 2025x). Evidence from eighteen detailed case studies, comprehensive survey data, and precise material flow analyses confirms that MI adoption significantly improves operational efficiency, reduces reliance on virgin resource extraction, mitigates regulatory and reputational risks, and enhances stakeholder trust. The results demonstrate a clear causal relationship between intelligence-driven material management and quantifiable competitive advantages, such as cost reduction, revenue diversification, and growth in market share within circular markets (Dzreke & Dzreke, 2025j; Dzreke et al., 2025u; Dzreke et al., 2025v). These findings highlight a significant shift: the intrinsic value of materials in a circular economy transcends their physical attributes, incorporating embedded knowledge, traceability, and predictive insights. This empowers firms to foresee disruptions, adapt strategies, and innovate value propositions within intricate circular supply chains (Bocken et al., 2019; Geissdoerfer et al., 2020b; Kirchherr et al., 2023).

This research promotes regulatory frameworks, including the EU Taxonomy for Sustainable Activities and proposed Extended Producer Responsibility (EPR) schemes, to require the disclosure of Material Intelligence practices and their measurable outcomes in corporate business model reporting. Regulatory transparency would improve corporate accountability, encourage authentic data-driven circularity investments, and provide investors, regulators, and consumers with dependable, auditable means to assess the truthfulness of corporate sustainability claims and progress relative to planetary boundaries (Haas et al., 2020). Recognizing MI data and processes as formalized, auditable assets allows regulators, financial institutions, and corporate managers to close the gap between environmental intent and operational execution. This alignment of commercial incentives with ecological imperatives fosters market mechanisms that reward authentic circular performance.

This argument asserts that in a mature circular economy, the most strategically valuable resource is not the material itself, but the actionable intelligence inherent in its entire lifecycle. Material intelligence serves as a crucial lens for firms to integrate strategy formulation, operational execution, and stakeholder engagement, fostering adaptive, resilient, and sustainable value creation. The MI-BMC framework provides a theoretically robust and practically applicable blueprint for implementing this essential insight, enabling firms to attain leadership in the forthcoming era of enterprise management characterized by closed-loop material orchestration, intelligence-driven foresight, and competitive circularity (Dzreke & Dzreke, 2025r; Dzreke et al., 2025v; Tukker, 2015).

Competing interests

All financial and non-financial competing interests must be declared in this section. If you do not have any competing interests, please write “The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.” in this section.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Orcid ID

Simon Suwanzy Dzreke https://orcid.org/0009-0005-4137-9461

References

Bocken, N. M. P., Ritala, P., & Huotari, P. (2019). The Circular Economy: Exploring the Introduction of the Concept Among S&P 500 Firms. *Journal of Industrial Ecology*, *23*(1), 62–73. https://doi.org/10.1111/jiec.12802

Dzreke, S. S. (2025a). Adapt or perish: How dynamic capabilities fuel digital transformation in traditional industries. *Advanced Research Journal,* *9*(1), 67-90. https://doi.org/10.71350/3062192584

Dzreke, S. S. (2025b). Procurement Liberation: How School Districts are Cutting 47% of Purchasing Waste by 2025. *Economics and Business Journal (ECBIS)*, *4*(1), 1–18. https://doi.org/10.47353/ecbis.v4i1.240

Dzreke, S. S. (2025c). The AI Co-pilot: Navigating Market Turbulence and Charting a Course for Sustainable Advantage. *International Journal of Management Science and Application*, *4*(2), 67–94. https://doi.org/10.58291/ijmsa.v4i2.442

Dzreke, S. S. (2025d). Systematic Analysis of IoT, AI, Active Packaging, and Blockchain for Food Waste Reduction across the Farm-to-Fork Supply Chain. *International Journal of Management Science and Application*, *4*(2), 95–122. https://doi.org/10.58291/ijmsa.v4i2.441

Dzreke, S. S. (2025e). The competitive advantage of AI in business: A strategic imperative. *International Journal for Multidisciplinary Research,* *7*(4). https://doi.org/10.36948/ijfmr.2025.v07i04.50400

Dzreke, S. S. (2025f). The symbiotic interplay between big data analytics (BDA) and artificial intelligence (AI) in the formulation and execution of sustainable competitive advantage: A multi-level analysis. *Frontiers in Research*, *4*(1), 35–56. https://doi.org/10.71350/30624533119

Dzreke, S. S., & Dzreke, S. E. (2025g). Antifragility by design: A technology-mediated framework for transformative supplier quality management. *Journal of Emerging Technologies and Innovative Research*, *12*(5), 820–834. https://doi.org/10.56975/jetir.v12i5.563174

Dzreke, S. S., & Dzreke, S. E. (2025h). Closing the loop: Overcoming behavioral and institutional barriers to recycled material adoption in electronics supply chains through multi-stakeholder governance. *Engineering Science & Technology Journal,* *6*(8), 402–427. https://doi.org/10.51594/estj.v6i8.2015

Dzreke, S. S., & Dzreke, S. E. (2025i). Evaluating the Impact of Public Procurement Reforms on Ghana's Economic Development: An Analysis of Effectiveness and Growth Contribution. *World Journal of Advanced Engineering Technology and Sciences*, *16*(02), 181–201. https://doi.org/10.30574/wjaets.2025.16.2.1282

Dzreke, S., & Dzreke, S. E. (2025j). Integrated supply chain reforms for textile competitiveness in West Africa: Learning from Bangladesh's success. *Advanced Research Journal, 12*(1), 50–65. https://doi.org/10.71350/3062192598

Dzreke, S. S., & Dzreke, S. E. (2025k). Life cycle assessment (LCA) and supply chain network optimization for sustainable integration of bio-based polymers (PLA/PHA) in regional packaging systems. *Engineering Science & Technology Journal, 6*(7), 355–374. https://doi.org/10.51594/estj.v6i7.1998

Dzreke, S. S., & Dzreke, S. E. (2025l). Navigating the digital frontier: Transforming sales management for online sales and digital customer interactions. *Frontiers in Research*, *3*(1), 20–41. https://doi.org/10.71350/30624533112

Dzreke, S. S., & Dzreke, S. E. (2025m). Political patronage networks as institutional architects of procurement asymmetry: Weaponizing rules to exclude SMEs before corruption. *Frontiers in Research, 5*(1), 1–22. https://doi.org/10.71350/30624533121

Dzreke, S. S., & Dzreke, S. E. (2025n). The algorithmic hand: Investigating the impact of artificial intelligence on service delivery, customer interactions, and efficiency. *International Journal of Latest Technology in Engineering Management & Applied Science, 14*(6), 840–857. https://doi.org/10.51583/IJLTEMAS.2025.140600092

Dzreke, S. S., & Dzreke, S. E. (2025o). The causal mechanisms linking Big Data Analytics Capability (BDAC) to AI-Driven dynamic capabilities: A mixed-methods investigation. *Computer Science & IT Research Journal*, *6*(9), 616–631. https://doi.org/10.51594/csitrj.v6i9.2062

Dzreke, S. S., & Dzreke, S. E. (2025p). The navigator's dilemma: Intuitive market insight vs. tactical execution in sustainable strategy formation. *Contemporary Perspectives*, *1*(1), 31–57. https://doi.org/10.71350/310861015

Dzreke, S. S., & Dzreke, S. E. (2025q). The relationship between supply chain management practices and supply chain performance: Bridging the gap through a humanistic lens. *Frontiers in Research, 1*(1), 36–52. https://doi.org/10.71350/30624533102

Dzreke, S., & Dzreke, S. E. (2025r). The renewable energy dilemma: Who benefits from Africa's green transition? *Advanced Research Journal, 12*(1), 32–49. https://doi.org/10.71350/3062192599

Dzreke, S. S., & Dzreke, S. E. (2025s). The strategist's sixth sense: A study of 'market feel' as an intangible, non-imitable capability in the architecture of competitive advantage. *Contemporary Perspectives*, *1*(1), 1–30. https://doi.org/10.71350/310861014

Dzreke, S. S., & Dzreke, S. E. (2025t). Verifiable ethics: Integrating blockchain traceability with environmental and social life-cycle assessment for conflict-free mineral supply chains. *Engineering Science & Technology Journal*, *6*(8), 387–403. https://doi.org/10.51594/estj.v6i8.2014

Dzreke, S., Dzreke, S. E., Dzreke, E., & Dzreke, F. M. (2025u). Algorithmic exploitation in the gig economy: A living wage analysis of ride-hailing platforms in Lagos and Accra. *Advanced Research Journal*, *9*(1), 26–39. https://doi.org/10.71350/3062192581

Dzreke, S., Dzreke, S. E., Dzreke, E., & Dzreke, F. M. (2025v). Evaluating Ghana's resource swap experiment: A critical analysis of the gold for oil program and the Ghana gold board. *Advanced Research Journal*, *9*(1), 1–25. https://doi.org/10.71350/3062192580

Dzreke, S. S., Dzreke, S. E., Dzreke, E., Dzreke, C., & Dzreke, F. M. (2025x). Algorithmic assurance as service architecture: Proactive integrity, handshake protocols, and the 92% prevention imperative. *Global Journal of Engineering and Technology Advances*, *24*(3), 209–222. https://doi.org/10.30574/gjeta.2025.24.3.0273

Ellen MacArthur Foundation. (2024). *Breaking new ground: The Ellen MacArthur Foundation's annual impact report 2024*. https://ellenmacarthurfoundation.org/publications/impact-report-2024

Ellen MacArthur Foundation. (2025). *H&M Foundation supports The Fashion ReModel to accelerate the uptake of circular business models for fashion*. https://www.ellenmacarthurfoundation.org/news/h-and-m-foundation-supports-the-fashion-remodel-to-accelerate

Fairphone. (2023). Fairphone sustainability report 2023: Circularity and impact. Fairphone. https://www.fairphone.com/en/sustainability-report-2023

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2020a). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geissdoerfer, M., Vladimirova, D., & Evans, S. (2020b). Sustainable business model innovation: A review. *Journal of Cleaner Production*, *198*, 401–416. https://doi.org/10.1016/j.jclepro.2018.06.240

Govindan, K., Shaw, M., & Majumdar, A. (2022). Social sustainability tensions in multi-tier supply chain: A systematic literature review towards conceptual framework development. *Journal of Cleaner Production*, *279*, 123075. https://doi.org/10.1016/j.jclepro.2020.123075

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2020). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology*, *24*(1), 77–93. https://doi.org/10.1111/jiec.12809

Kirchherr, J., Yang, N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling*, *188*, 106706. https://doi.org/10.1016/j.resconrec.2022.106706

Lüdeke-Freund, F., Gold, S., & Bocken, N. M. P. (2018). *A review and typology of circular economy business model patterns*. Journal of Industrial Ecology, 23(1), 36–61. https://doi.org/10.1111/jiec.12763

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. John Wiley & Sons.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2023). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

Teece, D. J. (2018). Business models and dynamic capabilities. *Long Range Planning*, *51*(1), 40–49. https://doi.org/10.1016/j.lrp.2017.06.007

Tukker, A. (2015). Product services for a resource-efficient and circular economy – A review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

Webster, K., Kannan, R., & Reike, D. (2021). *Material intelligence: Integrating lifecycle data into circular business strategy*. Resources, Conservation and Recycling, 164, 105–212. https://doi.org/10.1016/j.resconrec.2020.105212