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Big Data Analytics-Artificial Intelligence Capability and Circular Economy Adoption: Evidence from Pakistan's Automobile Sector

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ABSTRACT

This study examines whether big data analytics-artificial intelligence (BDA-AI) significantly affects circular economy (CE) adoption in Pakistan's automobile sector. A single hypothesis was tested using a cross-sectional survey design. Data were collected through a structured, adapted questionnaire from 396 valid respondents drawn from 19 automobile-sector firms operating in Pakistan. CE adoption was measured through a five-item scale reflecting reduce, reuse, recycle, recover, and regenerate practices, while BDA-AI capability was measured using items adapted from prior literature. Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). Reliability and validity criteria were broadly satisfied, with a combined Cronbach's alpha of 0.92, composite reliability values of 0.727 (BDA-AI) and 0.701 (CE), and average variance extracted values of 0.620 (BDA-AI) and 0.743 (CE). The hypothesized path from BDA-AI to CE was statistically significant ($\beta = 0.014$, $t = 2.745$, $p = 0.006$), supporting the hypothesis, although the path coefficient itself was small in magnitude. The findings suggest that BDA-AI capability is positively associated with CE adoption among automobile-sector firms in Pakistan, but the modest effect size indicates that technology adoption alone is unlikely to drive substantial circularity gains without complementary organizational and contextual support. This is among the first studies to empirically test this relationship within Pakistan's automobile sector.

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1. Introduction

Pakistan's automobile sector has a strategic position in the industrial base, contributing towards employment, manufacturing, and export, while simultaneously confronting mounting pressure to curb resource usage and environmental damage. Prior research has documented that firms in the automobile sector in Pakistan recognize profitability, cost reduction, and environmental sustainability as driving forces for adopting the circular economy (CE), but are constrained by illiteracy, unawareness, and financial constraints, and a deficiency of expertise (Agyemang, Kusi-Sarpong, Khan, Mani, Rehman, & Kusi-Sarpong, 2019). These obstacles point toward a capability gap: firms may be tempted to transition toward circularity but fail due to a lack of informational and analytical capacity to identify, monitor, and act on circular opportunities across production, distribution, and consumption processes.

Digital technologies, particularly big data analytics powered by artificial intelligence (BDA-AI), stood as a resource helping firms minimize this capability gap. BDA-AI allows firms to integrate information from sources, apply analytical techniques leading to simulation and optimization, and demonstrate complex information for the sustenance of decision-making. Evidence related to automotive firms indicates that BDA-AI capability leads to the development of sustainable manufacturing and a circular economy (Bag, Pretorius, Gupta, & Dwivedi, 2021). In Pakistan, research has explored the contribution of artificial intelligence to circular economy transitions in the agriculture and food sectors (Ali, Zain, Pathan, & Mooney, 2024), but empirical evidence linking BDA-AI capability to CE practices adoption within the automobile sector remained underexplored.

The current study addresses the gap by investigating the following hypothesis in the context of Pakistan's automobile industry:

H1: BDA-AI has a positive effect on Circular Economy (CE) adoption in Pakistan's automobile industry.

2. Literature Review and Hypothesis Development

The utilization of I4.0 technology (BDA-powered AI) has a positive correlation with circular economy capabilities [121]. The works provided by Jabbour et al. (2020) also strengthen this Data, especially the solutions of reduce, reuse, and recycle-based manufacturing, which are the main elements for attaining circularity abilities (Tseng). The latest I4.0 technology has the potential to improve the implementation of the CE by unleashing the circularity of supplies in the system (Jabbour et al., 2020). The service structure as well as policy support of are known to be major enablers that may combine I4.0 and CE. Work suggested by [131] supports I4.0 technologies that favor CE utilization.

Although the world's progress is at an unmatchable pace today. A huge urbanization has marked the era with an increased use of technology and AI-based tools to make businesses competitive. Hence, it requires an equivalent and parallel effort to mitigate the environmental hazards created by building progress. Recently, floods and other natural hazards, along with a global warming situation, have alarmed the world about the disastrous effects of industrialization and urbanization at large. Therefore, a global wave of retaining and reinstating the environment has started. One good example is Sustainable Development Goals (SDG-17) presented and supported by the United Nations (UN) and pertaining to their agenda of 2030 to save the world. The 17 goals under SDG are bifurcated to cover all harms that can be controlled and cured. Many countries are supporting and working towards these goals, but the progress in rebuilding is slow. As previously discussed, recent industry statistics reveal that the automobile industry is a significant contributor to this situation.

The resource-based view (RBV) argues that firms achieve sustained competitive advantage by developing and deploying resources and capabilities that are valuable, rare, and difficult to imitate (Barney, 1991). Building on this logic, the dynamic capabilities perspective emphasizes that firms must continuously sense opportunities, seize them, and reconfigure internal resources and processes to respond to a changing environment (Teece, 2007). BDA-AI capability can be understood through this lens as a digital resource that strengthens a firm's capacity to sense inefficiencies, seize circular opportunities, and reconfigure production and supply chain processes accordingly. Firms with stronger BDA-AI capability can more easily combine data from multiple sources, apply advanced analytical and predictive techniques, and use dashboards and visualization tools to support root-cause analysis and continuous improvement, all of which are relevant to identifying and acting on circular opportunities.

Empirical support for this can be found Bag et al. (2021), BDA-AI capability, shaped by institutional pressures and firm resources, contributed to sustainable manufacturing practices and circular economy capabilities among automotive and allied manufacturing firms. More broadly, AI demonstrated to support for circular economy transitions by enabling predictive maintenance, waste reduction, and more efficient resource use across manufacturing and agri-food contexts (Ali et al., 2024). At the same time, research specific to Pakistan's automobile sector has shown that CE implementation continues to be hindered by a lack of awareness, financial constraints, and limited technical expertise (Agyemang et al., 2019), which suggests that the translation of BDA-

AI capability into circular outcomes may be weaker in Pakistan's automobile sector than in more digitally mature manufacturing contexts.

Taken together, theory suggests a positive relationship between BDA-AI capability and CE adoption, while contextual evidence from Pakistan's automobile sector suggests this relationship may be constrained. This study tests the direction and significance of this relationship directly:

H1: BDA-AI capability has a significant positive effect on CE adoption in Pakistan's automobile sector.

3. Research Methodology

3.1 Research Design

This study adopted a quantitative, cross-sectional survey design to test the hypothesized relationship between BDA-AI capability and CE adoption.

3.2 Sample and Data Collection

Data were collected from employees and managers (including operations, procurement, supply chain, logistics, and plant-level managers) working across 19 automobile-sector firms operating in Pakistan. A total of 396 valid responses were retained for analysis after data screening.

3.3 Measures

CE adoption was measured using a five-item reflective scale (CE1–CE5) capturing the extent to which the organization is engaged in reducing, reusing, recycling, recovering, and regenerating resources across production, distribution, and consumption processes. BDA-AI capability was measured using items adapted from prior big-data-analytics-and-artificial-intelligence capability literature (Bag et al., 2021), covering the use of advanced analytical techniques, the integration of data from multiple sources, and the use of data visualization and dashboard tools to support decision-making. All items were measured on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). During measurement model assessment, two BDA-AI indicators (BDA-AI4 and BDA-AI5) were removed due to insufficient outer loadings, resulting in a retained set of eight BDA-AI indicators; all five CE indicators were retained.

3.4 Data Analysis Technique

Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to test the measurement model and the hypothesized structural path. PLS-SEM is well suited to prediction-oriented research involving reflective measurement models and is widely used in management and sustainability research for testing single or multiple hypothesized paths (Hair, Risher, Ringle, & Sarstedt, 2019). The measurement model was assessed for internal consistency reliability (Cronbach's alpha and composite reliability) and convergent validity (average variance extracted), followed by an assessment of the structural path using the bootstrapping resampling procedure recommended for PLS-SEM analysis.

4. Data Analysis and Results

4.1 Measurement Model Assessment

Table 1 presents the reliability and convergent validity results for the two constructs. The combined Cronbach's alpha across the retained items was 0.92, indicating strong overall internal consistency. At the construct level, composite reliability (CR) was 0.727 for BDA-AI and 0.701 for CE. Both values exceed the conventional minimum threshold of 0.70 (Hair et al., 2019), though the CE construct's CR is only marginally above this threshold and should be interpreted with some caution. Average variance extracted (AVE) was 0.620 for BDA-AI and 0.743 for CE, both comfortably exceeding the recommended minimum of 0.50, indicating adequate convergent validity for both constructs.

Construct	Items Retained	Cronbach's Alpha	Composite Reliability (CR)	AVE
Big Data Analytics-Artificial Intelligence (BDA-AI)	8	0.92 (combined)	0.727	0.620
Circular Economy (CE) Adoption	5	0.92 (combined)	0.701	0.743

4.2 Structural Model Assessment and Hypothesis Testing

Table 2 presents the results of the structural path from BDA-AI to CE. The path was statistically significant ($t = 2.745$, $p = 0.006$), providing support for H1. The original sample path coefficient was small ($\beta = 0.014$), while the bootstrap sample mean was somewhat higher ($M = 0.123$, $SD = 0.045$). This gap between the original coefficient and the bootstrap mean indicates some instability in the estimated effect size and suggests that, while the relationship is statistically detectable given the sample size, its practical magnitude is limited.

Hypothesized Path	Original Sample (β)	Sample Mean (M)	SD	t-value	p-value
H1: BDA-AI → CE	0.014	0.123	0.045	2.745	0.006

Overall, the results indicate that BDA-AI capability is positively and significantly associated with CE adoption among the surveyed automobile-sector firms in Pakistan, consistent with H1, though the strength of this association is modest rather than substantial.

5. Discussion

The finding that BDA-AI capability significantly predicts CE adoption is broadly consistent with the resource-based and dynamic capabilities logic underlying this study, and aligns directionally with evidence from automotive firms in South Africa, where BDA-AI capability was found to support sustainable manufacturing and circular economy capabilities (Bag et al., 2021). This suggests that the theoretical mechanism, whereby data integration, analytical techniques, and visualization tools help firms identify and act on circular opportunities, extends, at least partially, to Pakistan's automobile sector.

At the same time, the small magnitude of the path coefficient suggests that BDA-AI capability alone explains only a limited portion of the variation in CE adoption among the firms studied. This is consistent with earlier findings that CE implementation in Pakistan's automobile industry is constrained less by a lack of motivation and more by unawareness, cost and financial constraints, and limited technical expertise (Agyemang et al., 2019). Firms may possess some level of BDA-AI capability without having the complementary organizational knowledge, financial resources, or managerial commitment required to translate that capability into meaningful circular practices.

This interpretation is consistent with the dynamic capabilities view, which holds that sensing capability alone is insufficient without the capacity to seize opportunities and reconfigure organizational processes accordingly (Teece, 2007).

The borderline composite reliability of the CE construct (0.701) also warrants some caution in interpreting the strength of this relationship, and future replications using a more extensively validated CE scale would help confirm whether the modest effect size reflects a genuine contextual constraint or, in part, measurement limitations.

6. Conclusion, Implications, Limitations, and Future Research

This study set out to test whether BDA-AI capability significantly affects CE adoption within Pakistan's automobile sector. Using survey data from 396 respondents across 19 firms and PLS-SEM analysis, the hypothesized relationship was supported, though the effect size was small. This provides preliminary evidence that digital analytical capability is a relevant, but not sufficient, condition for advancing circular economy practices in this sector.

Theoretically, this study extends the resource-based and dynamic capabilities literature on BDA-AI and circular economy capabilities (Bag et al., 2021) to a new emerging-market context, offering one of the first direct empirical tests of this relationship within Pakistan's automobile sector. Practically, the findings suggest that managers and policymakers should not treat investment in big data analytics and artificial intelligence tools as sufficient, on its own, to drive circular economy outcomes. Complementary investment in employee digital literacy, managerial commitment, and financial support may be necessary to help firms convert analytical capability into circular practice, particularly in light of previously documented barriers of unawareness, cost, and expertise in this sector (Agyemang et al., 2019).

This study has several limitations. First, the cross-sectional, single-country, single-sector design limits the generalizability of the findings to other sectors or contexts. Second, the small magnitude of the path coefficient, together with the borderline composite reliability of the CE construct, suggests the results should be interpreted with caution rather than as strong confirmation of a substantial effect. Third, the 396 respondents were nested within only 19 firms; treating individual responses as fully independent observations does not account for this clustering, and future studies may benefit from multi-level modeling approaches. Fourth, the study relied on a single hypothesis and did not include control variables (such as firm size or firm age) or contextual moderators (such as institutional pressures or organizational flexibility) that have been shown to matter in related research (Bag et al., 2021). Future research should test this relationship with larger and more heterogeneous samples, incorporate relevant control variables and moderators, and examine additional outcome variables such as sustainable manufacturing performance, to build a more complete understanding of how digital capabilities support circular economy adoption in Pakistan's automobile sector.

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