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Leveraging Big Data Analytics: AI for Circular Economy through Absorptive Capacity

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Abstract

This study builds a comprehensive investigation framework on how Big Data Analytics–Artificial Intelligence (BDA-AI) drives Circular Economy (CE) adoption through mediating into dynamic capability theory. The study argues that technology does not establish outcomes by itself; besides, outcomes develop from how technology is interpreted and adapted in social contexts. The current study contributes to existing literature by integrating BDA-AI with ACAP and circular innovation. The phenomenon is explored through the automobile industry of Pakistan. Empirical evidence supports the model of study for a complete mediation signifying an indirect value of 0.89 and a Cronbach's alpha value of 0.787. Findings establish that, although technology investment is significantly related to circular economy practices adoption, the knowledge absorptive capacity enhancement cannot be ignored to achieve those outcomes. The study has used dynamic capability theory to support the hypothesis of the study.

Keywords: absorptive capacity, BDA-AI, circular economy, dynamic capability theory

Introduction

Although the automobile sector has been a major contributor to economic strength, the degrading impact it has on the environment is high (Johri & Petison, 2008). The automobile industry in Pakistan is also developing; therefore, designing and implementing environmentally friendly practices will be beneficial. Recycling has been established to reduce waste production, leading to resource conservation. Hence, the circular economy is not an option but a requirement (He et al., 2023; Tseng et al., 2018). In recent years, organizations have significantly invested in Big Data Analytics and Artificial Intelligence to enhance efficiency, innovation, and

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competitiveness. Simultaneously, the global shift toward sustainability has intensified the need for firms to adopt Circular Economy practices that minimize waste and optimize resource utilization (Bag et al., 2022; Doghan et al., 2025). Despite a rapid infusion of digitalization, firms might fail to effectively transform the BDA-AI capabilities they hold into sustainable outcomes, leading to the failure of many small enterprises after a very short period of their startup (Chen et al., 2024).

The above disconnect discloses a significant gap in prior literature. While earlier studies have investigated the direct effect of digital technologies on the performance of a firm, scarce attention has been paid to the underlying mechanisms enabling the reconfiguration of data-driven insights into circular practices. Specifically, there is a limited understanding of how firms adopt, process, and exploit any knowledge derived from BDA-AI (Chen et al., 2024).

The current study addresses this gap by hypothesizing absorptive capacity (ACAP) as a key explanatory mechanism for how firms transform technological capabilities into outcomes related to the circular economy. Focusing on this mechanism, this study responds to calls for a more nuanced and process-oriented theoretical explanation related to technological transformation and sustainability literature.

In this scenario, the current study uses an explanatory mechanism that firms might adopt to investigate how BDA-AI shapes the CE adoption through ACAP. Table 1 below demonstrates the operational definitions of the variables used in the study.

Table 1

Operational Definition of Constructs of the Study

Variable	Operational Definition	Author	Type
Big Data Analytics-Artificial Intelligence (BDA-AI)	BDA-AI is defined as 'technologies (e.g., database and data mining tools) and techniques (e.g., analytical methods) that a company can employ to analyze large-scale, complex datasets to perform data-driven decision-making for predictive, prescriptive, and automated intelligence (Hossain et al., 2024). It's a unidimensional variable.	(Dubey, Gunasekaran, & Childe, 2019)	Reflective

Variable	Operational Definition	Author	Type
Absorptive Capacity (ACAP)	Absorptive Capacity refers to an organization's ability to recognize the value of new external knowledge, acquire it, assimilate it into existing processes, and apply it to achieve commercial, operational, or innovative outcomes (Cohen & Levinthal, 1990). It's a unidimensional variable.	(Flatten et al., 2011)	Reflective
Circular Economy (CE)	Circular Economy Practices refer to organizational strategies and operational activities aimed at minimizing resource use, extending product lifecycles, and closing material loops through reuse, recycling, remanufacturing, and sustainable design, with the goal of achieving environmental sustainability and economic efficiency. These practices focus on reducing waste generation, optimizing resource efficiency, and creating regenerative production-consumption systems (Yasmeen & Longsheng, 2025). It's a unidimensional variable.	(Geissdoerfer et al., 2017)	Reflective

Hypotheses Development

Big Data Analytics–AI

In the contemporary business world, data has emerged as a resource, with organizations taking up the digitalization route for their operation and generating a huge amount of data (Chen et al., 2025). This big data is useless without having any tools to configure it as useful. BDA-AI encapsulates the significant capability of a firm, enabling organizations to process huge volumes of data that is either structured or unstructured. Wamba et al. (2015) conceptualized a firm's BDA capability as a mix of tangible, human, and other intangible resources that collectively increase the performance of an organization. Studies established that AI-driven predictive decision-making and support systems bring operational efficiency and innovation (Chen et al., 2018; Wamba et al., 2015; Kwon et al., 2014; Zong et al., 2025). BDA-AI increases a firm's capability to access, evaluate, and translate huge amounts of data, thereby strengthening its capacity to acquire, assimilate, transform, and exploit data insights. If such diverse knowledge is not accessible, absorptive capacity (ACAP) cannot develop.

H1: BDA-AI positively affects absorptive capacity.

Circular Economy

Since climate change is a global issue, environmental protection has been upgraded on the international agenda. Corporations must compete and improve an environment protection policy and bring it to the attention of stakeholders (Ghisellini et al., 2016). It is not only the responsibility of the governments but also the industry to highlight concerns and solutions related to environmental sustainability. One such idea is to introduce the circular economy into the production cycle of major firms. The automobile industry can be a catalyst in achieving this goal. The Circular Economy (CE) emphasizes sustainable production and consumption through resource efficiency, reusability, and recycling (Sondh et al., 2024). The notion of circular economy (CE) gained momentum among managers, businesses, policymakers, and academicians due to its potential contribution towards sustainable development (Geissdoerfer et al., 2017). Advanced digital technologies might be critical enablers of CE by tracking the products, parts, and raw materials, and making the data available for optimized resource management across divergent stages of the industry (Sondh et al., 2024). Circular economy stands as a key policy strategy to decrease the environmental impact of social frontiers.

Despite a plethora of available literature on the relationship between digital technologies and the circular economy (Antikainen et al., 2023; Bag & Pretorius, 2022; Chen et al., 2024; Kristoffersen et al., 2020; Maghsoudi et al., 2025), additional insights are required (Chauhan et al., 2022), as it has become more important to explore the mechanisms through which technologies play their part in establishing CE through enhancing skills.

H2: Absorptive capacity positively influences circular economy practices.

Absorptive Capacity

Absorptive capacity is a firm's ability to identify, integrate, interpret, and employ external knowledge (Cohen & Levinthal, 1990) to transform an organization and enhance its innovation potential. This refers to a firm’s effort to absorb the change in the internal and external environment, and reflect the potential in its production processes and business innovation model. Zahra and George (2002) further bring a conducive ideology that a dynamic capability is a resource enabling knowledge transformation and the exploitation of skills into the adoption of practices. Empirical studies highlight its role in innovation, learning, and competitive advantage.

A prerequisite for bringing innovations to a firm is its absorptive capacity (Stelmaszczyk et al., 2023). Absorptive capacity (ACAP) is the assimilation of knowledge into valuable information to build commercial benefits. ACAP assists in the generation of new information through BDA-AI, leading to capability creation (Dhamija & Bag, 2020). An increase in the absorptive capacity helps in better system establishment. Therefore, ACAP is another organizational resource to build the infrastructure of the firm (Bag et al., 2024), and to improve this resource investment, data analytics is crucial.

BDA-AI brings analytics to generate insights about huge data, but these insights need to bring implementable implications (Zong et al., 2025). Absorptive capacity determines if those insights are comprehended, adopted, and transubstantiated into circular economy adoption (Harvey et al., 2010; Martinez-Sanchez & Lahoz-Leo, 2018). BDA-AI enables processing huge amounts of data related to the environment and operations, identifying inefficiencies and resource loops to generate predictive analytics leading to sustainable outcomes in the future (Chen et al., 2012, 2018; Chen & Zhang, 2014). Conversely, data is not action, and firm managers are looking for actionable insights. Most of the firms fail not because of data unavailability but due to the inability to interpret and employ that data in a useful way (Amankwah-Amoah & Adomako, 2019). Therefore, strong learning mechanisms need to be developed along with knowledge integration. This makes absorptive capacity a critical factor for firms to utilize external knowledge, stimulating internal innovation.

The current study argues that firms become circular not because they implement BDA-AI, but because they build the organizational absorptive capacity to adopt and act upon data insights. Hence, it is hypothesized that:

H3: Absorptive capacity mediates the relationship between BDA-AI and CE.

Table 2

RQs, Ros and Hypotheses of the Study (Authors conceptualization)

1	Does BDA-AI effect the ACAP of the organization?	To explore the relationship between BDA-AI and Absorptive Capacity (ACAP)	Hypothesis 1: BDA-AI has a significant relationship with the ACAP of the organization
2	Does ACAP effect CE?	To explore the relationship between Absorptive Capacity (ACAP) and Circular Economy (CE).	Hypothesis 5: ACAP has a significant effect on CE.
3	Does BDA-AI effect CE?	To investigate the relationship between BDA-AI and CE.	Hypothesis 7: There is a significant relationship between BDA-AI and CE.
4	Does ACAP plays a mediating role between BDA-AI and CE?	To investigate the mediating role of ACAP between BDA-AI and CE	Hypothesis 9: ACAP has a significant mediating effect between BDA-AI and CE.

Integrative Perspective

Although BDA-AI extracts valuable insights through resource optimization and waste management, its effectiveness is linked to the firm's ability to interpret and apply that knowledge. Absorptive capacity (ACAP) is the capability to bring transformation through knowledge integration and practical demonstration, resulting in a support of circular economy initiatives by industry leaders and the government. This research integrates these streams, offering a holistic view of how digital capabilities and technology dynamics translate into an environmentally friendly, sustainable outcome. Mediation of study is supported on the assumption of Preacher and Hayes (2004).

Theoretical Framework

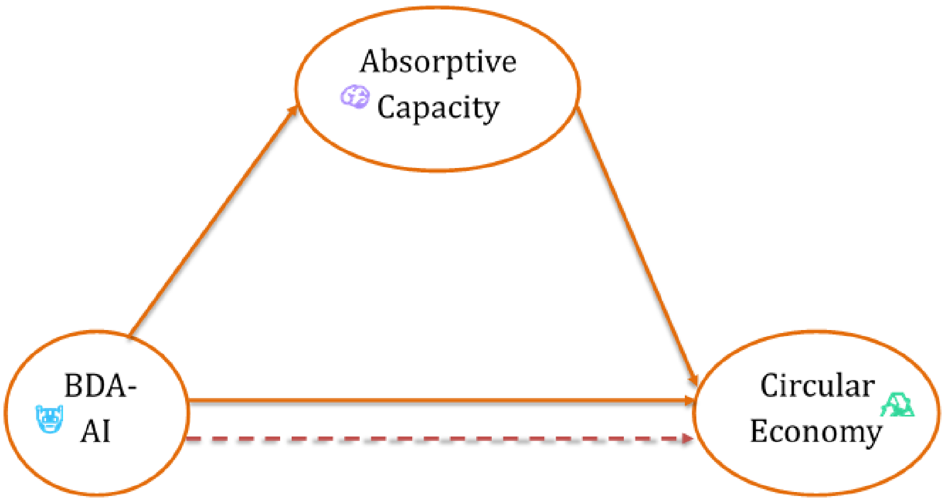
Dynamic Capability Theory

The conceptualization of the model of the study is grounded in Dynamic Capability Theory (DCT). It is referred to as a firm’s capability to adapt, integrate, and reconfigure its resources, both internal and external, to cope with the changing needs of the environment (Teece et al., 1997). There are 3 key components of this theory: sensing, seizing, and transforming. BDA-AI identifies opportunities and system inefficiencies that build its sensing capability.

ACAP, being the knowledge processing capability of the employees, is the transforming capability, and finally, circular economy is the resultant change that is observed as a reconfiguration of the outcome. Hence, ACAP stands as a necessary transmission mechanism and not just another predictor of the phenomenon. Firstly, firms are exposed to real-time data analytics, predictive sustainability comprehensions and insights, and resource data for the next step. Secondly, change agents in the firm interpret AI output, determine sustainability relevance, and, based on this insight, they develop a shared understanding of the phenomenon. If this phase is not considered, insights from the data remain fragmented. Thirdly, new insights are combined with existing operations and processes, routines are reconfigured, and new operational logics are implemented. Finally, on the basis of new operational logics, recycling systems are introduced along with resource optimization. This is also referred to as the knowledge exploitation phase of the theory. Absorptive Capacity (ACAP) translates BDA-AI from a mere data-processing capability to a sustainability-oriented dynamic capability driving circular economy outcomes.

Figure 1

Conceptual Model of the Study



Research Method

The data collection of the study was done through the distribution of a questionnaire. All the scales were adopted after validating them from the previous studies (Hair et al., 2017). To design the questionnaire, academic literature was reviewed, authors investigated the items most representative of study constructs. To ensure the highest reliability, the research picked items only from empirical studies. The scale for measuring BDA-AI was obtained from Bag et al. (2020) and the scale for ACAP was adopted from Camisón and Forés (2010), the scale for CE was adopted from Hassan et al. (2023).

Table 3
Scales of the constructs

Variable	Scale (Author)	Type
Big Data Analytics-Artificial Intelligence (BDA-AI)	(Bag et al., 2020)	Reflective
Absorptive Capacity (ACAP)	(Camisón & Forés, 2010)	Reflective
Circular Economy (CE)	(Hassan et al., 2023)	Reflective

Figure 2
Research Onion Saunders et al., (2016)

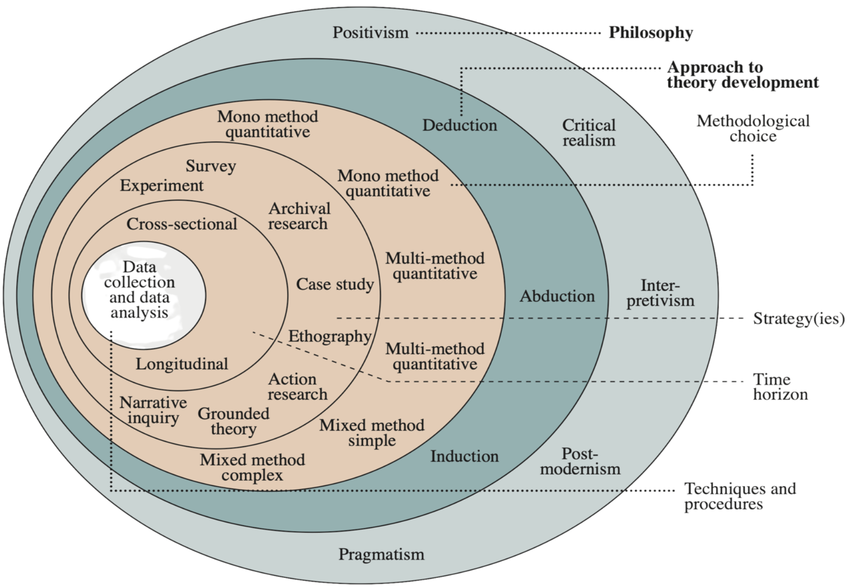


Table 4
Response Rate of the Study

Description	Number
Questionnaires Distributed/shared links	450
Questionnaires Returned	423
Incomplete Questionnaires	16
Questionnaires Excluded (Outliers / Missing Data)	11
Final Usable Questionnaires	396
Response Rate	88%
Usable Response Rate	88% (396/450)

The population of the study was the automobile industry of Pakistan. As it has been established in previous research that this industry is one of the most waste-generating industries, since the required data needs a particular level of knowledge, data was collected from only middle and top-level executives of those organizations. Respondent firms were selected from the Pakistan Automobile Manufacturing Association (PAMA) list available online. A total of 450 questionnaires were distributed, including both printed, and a shared link; out of that, 423 were returned. From the returned questionnaire, 16 had incomplete responses, and 11 had missing values, leaving behind a total of 396 observations.

Table 5
Descriptive Statistics

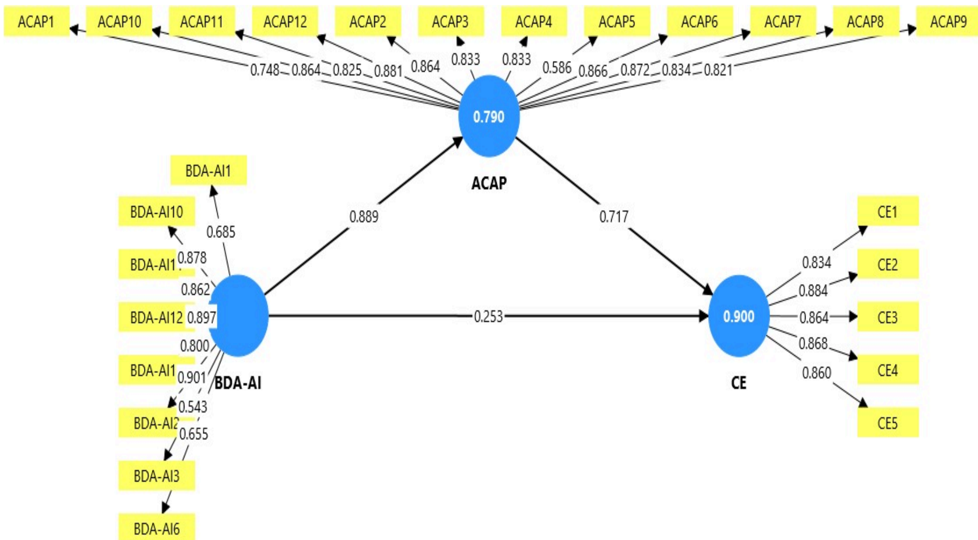
Variables	Median	Min	Max	Kurtosis	Skewness	Cramér-von Mises	*p* value
Absorptive _capacity	-0.561	-1.45	1.54	-1.86	0.09	6.479	0.000
BDA-AI	-0.056	-1.86	1.75	-1.48	-0.03	2.338	0.000
Circular Economy	-0.425	-1.44	1.535	-1.70	0.08	4.349	0.000

The constructs were standardized prior to data analysis using a z-score transformation, ensuring data fit and comparability across all the constructs of the study, and it also helped in reducing scale-related biases. A skewness value reported close to zero, which shows an almost symmetric distribution of data. An excess kurtosis showing a platokurtic distribution establishes that the data is flatter in its peak for a normal distribution. Hence, data is proved to be well-bounded and consistent. These tests, although established on normal data normality, yet are robust against non-normal distribution.

Table 5 shows the descriptive statistics related to study variables. The results demonstrate that all variables were standardized, with a mean value of zero and a standard deviation (S.D) of one. Skewness values ranged from −0.027 and 0.088, predicting a symmetric distribution; kurtosis values showed a slightly platykurtic curve. Though the output from the Cramér–von Mises test was statistically significant (at $p < 0.001$), this is normal given the large sample size.

Figure 3

Measurement Model of the Study



The results from the structural model of the study show that BDA-AI has a significant positive effect on ACAP ($\beta = 0.889$, $p < 0.001$), supporting Hypothesis (H1). Furthermore, ACAP significantly effects circular economy (CE) adoption ($\beta = 0.717$, $p < 0.001$), supporting Hypothesis 2 of the study. The mediation analysis shows a significant indirect effect of BDA-AI on circular economy (CE) through absorptive capacity ($\beta = 0.637$), confirming mediation. These results indicate absorptive capacity as an important mechanism explaining how digital capabilities lead to sustainability outcomes like CE.

All constructs showed a high reliability, with Cronbach's alpha values of 0.955 (ACAP), 0.908 (BDA-AI), and 0.914 (CE), meeting the recommended threshold of 0.70. These values confirm a strong internal consistency. Convergent validity is established by higher outer loadings and also the significant t-values. Moreover, Average Variance Extracted (AVE) values exceed the minimum threshold of 0.50, showing that the variable explains a substantial part of the variance. Discriminant validity of the constructs was established using the Heterotrait-Monotrait (HTMT) ratio.

The HTMT ratio is a measure of the distinctiveness of the constructs (Henseler et al., 2015). A value greater than or equal to 0.9 depicts a close correlation between the constructs of the study, and a value just equal to 1 establishes that the constructs are identical, which leads to invalidating a model to be tested for a relationship. In the current study, HTMT ratio values were below the required threshold of 0.85–0.90, validating constructs as empirically distinct.

The empirical results of the study provide strong support for the proposed framework of the study. A higher R^2 value further showed significant explanatory power of the model, especially in predicting ACAP. These empirical highlights address a major limitation of previous literature, which often assumed a direct relationship between technology and sustainability (Dubey, Gunasekaran, Childe, et al., 2019; Nogueira et al., 2023; Song et al., 2017; Wu & Wang, 2024). The results showed that although BDA-AI provides the knowledge foundation of sustainability, it still enables firms to transform these knowledge and insights into actionable circular economy adoption. Overall, the findings of the study fall in line with the grounded theory of the study.

Table 6

Path coefficients

	ACAP	BDA-AI	CE
ACAP			0.717
BDA-AI	0.889		0.253
CE			

Table 7

Indirect Effect

	Specific indirect effects
BDA-AI -> ACAP -> CE	0.637

Table 8
Model Fit

	Saturated model	Estimated model
SRMR	0.050	0.050
d_ULS	0.817	0.817
d_G	1.335	1.335
Chi-square	2178.765	2178.765
NFI	0.797	0.797

Table 9
Path Coefficients

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	*p*
ACAP -> CE	0.717	0.717	0.032	22.619	0
BDA-AI -> ACAP	0.889	0.889	0.01	92.462	0

Table 10
Cronbach Alpha

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	*p*
ACAP	0.955	0.955	0.002	556.305	0.00
BDA-AI	0.908	0.908	0.006	153.372	0.00
CE	0.914	0.913	0.005	177.925	0.00

Table 11
HTMT

	HTMT
BDA-AI <-> ACAP	0.646
CE <-> ACAP	0.406
CE <-> BDA-AI	0.568

Implications

Since a full mediation is established in the study, it is concluded that high BDA-AI alone cannot establish the path. If the ACAP of the firm is not increased in a synchronized way, it leads to data overload, decision paralysis, and ultimately misaligned sustainability initiatives. By positioning ACAP as a central mechanism, the current study advances a nuanced view of how digital capabilities are transformed into sustainable outcomes, offering theoretical and industrial insights into the future of a more data-driven circular economy. Highlighting circular economy implementation as a fundamentally knowledge-intensive area and process, it requires firms to comprehend, integrate, and implement composite information pertaining to sustainability. The mediation analysis showed that ACAP acts as a critical mechanism allowing BDA-AI to lead to circular economy outcomes. These findings extend the work by Cohen and Levinthal (1990), establishing relevance in the context of AI-based sustainable transformations. Hence, empirical evidence in this study brings a valuable theoretical contribution. In the future, researchers can extend this study by analysing longitudinal data to ensure the generalizability of the model. A moderating variable, line environmental dynamism, can add valuable insights to the study. Data from other sectors can also be used to check the explanatory power of the model.

Author Contribution

Tasleem Malik: Conceptualization, Data curation, Methodology, Visualization, Writing-original draft, Validation. **Marria Hassan:** Supervision, Project administration, Investigation, Formal analysis, Resources, Software, Writing-review & editing

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

The data associated with this study will be provided by the corresponding author upon request.

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The authors did not use any type of generative artificial intelligence software for this research.

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