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Green Digital Technologies, Circular Economy Adoption, and Sustainable Business Performance: The Mediating Role of Eco-Innovation and the Moderating Role of Institutional Support

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Abstract

Green digital technologies are increasingly used to improve environmental visibility, resource efficiency, and sustainability-oriented decision-making. However, their association with sustainable business performance may depend on whether firms convert digital resources into organizational capabilities and implemented circular practices. Drawing on the Natural Resource-Based View, Dynamic Capabilities Theory, and Institutional Theory, this study examines a moderated serial mediation model in which eco-innovation and circular economy adoption sequentially mediate the relationship between green digital technologies and sustainable business performance, while institutional support moderates the relationship between eco-innovation and circular economy adoption. Survey data were collected from managers and professionals in Saudi industrial and manufacturing firms. Of the 450 questionnaires distributed, 420 were returned, and 386 usable responses remained after data-quality screening and were analyzed using partial least squares structural equation modeling in SmartPLS 4. The results show that green digital technologies are positively associated with eco-innovation ($\beta = 0.662$, $p < 0.001$) and circular economy adoption ($\beta = 0.263$, $p < 0.001$). Eco-innovation is positively associated with circular economy adoption ($\beta = 0.487$, $p < 0.001$), which, in turn, is strongly associated with sustainable business performance ($\beta = 0.726$, $p < 0.001$). The serial indirect association through eco-innovation and circular economy adoption is significant ($\beta = 0.234$, $p < 0.001$). Institutional support also strengthens the eco-innovation–circular economy adoption relationship, although the interaction is comparatively modest ($\beta = 0.118$, $p = 0.002$). The study contributes by distinguishing eco-innovation as a resource-conversion capability from circular economy adoption as an implemented organizational practice and by identifying institutional support as a boundary condition within Saudi industrial firms.

Keywords: green digital technologies; eco-innovation; circular economy adoption; sustainable business performance; institutional support; serial mediation; moderation; PLS-SEM

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1. Introduction

Digitalization and circular economy adoption are increasingly viewed as interdependent components of organizational sustainability rather than as separate transformation

agendas. Circular economy practices provide an environmental and operational purpose for digital investments by supporting waste prevention, resource efficiency, product-life extension, reverse flows, and closed-loop operations. In parallel, digital technologies provide the visibility, connectivity, traceability, and analytical capacity required to monitor material and energy flows and coordinate sustainability-oriented decisions across organizational and supply-chain boundaries [1–5]. However, the availability of digital technologies does not necessarily correspond to stronger sustainability performance. Their organizational value depends on how firms use digital information to redesign products, processes, and operating models.

Green digital technologies refer in this study to the sustainability-directed application of digital systems rather than to general organizational digitalization. Such technologies may include artificial intelligence, the Internet of Things, big data analytics, blockchain, digital twins, and smart monitoring systems when they are applied to environmental monitoring, energy optimization, waste reduction, lifecycle management, predictive maintenance, and reverse-flow coordination. This distinction is important because technology should not be characterized as environmentally beneficial merely because it is digitally advanced. Its relevance to sustainability depends on whether its application supports identifiable environmental or circular objectives [6–8]. Previous research has generally supported positive relationships among digitalization, environmental innovation, circular economy practices, and organizational performance. Nevertheless, the reported relationships are not uniform across firms and contexts. Digital investments may generate limited sustainability value when they remain isolated from organizational routines, when employees lack the capability to use environmental information, or when circular initiatives face financial, infrastructural, regulatory, and interorganizational barriers. Existing studies have frequently examined direct relationships between digital technologies and performance or between circular economy practices and business outcomes [9–12]. This emphasis leaves the organizational conversion process insufficiently explained: digital resources may reveal inefficiencies, but they do not independently redesign products, alter production processes, establish reverse logistics, or institutionalize closed-loop practices.

This study addresses this limitation by distinguishing eco-innovation from circular economy adoption and positioning them sequentially within the same explanatory model. Eco-innovation is conceptualized as an organizational capability through which firms convert sustainability-related information into environmentally improved products, processes, technologies, and managerial routines. Circular economy adoption, in contrast, represents the implementation of observable practices such as resource reduction, reuse, recycling, recovery, circular procurement, product-life extension, and closed-loop operations. The distinction is theoretically important because an organization may possess innovation-oriented capabilities without successfully embedding circularity in its day-to-day operations. Accordingly, the proposed sequence suggests that green digital technologies are associated with greater eco-innovation, which is associated with stronger circular economy adoption and, subsequently, sustainable business performance.

The study further argues that the transition from eco-innovation to circular economy adoption is contingent on institutional support. Eco-innovation can originate within the firm through managerial commitment, technical knowledge, and organizational experimentation. Its conversion into implemented circular practices, however, often requires conditions that extend beyond firm boundaries, including regulatory clarity, financial incentives, technical standards, training, infrastructure, and collaboration with external stakeholders. Institutional support is therefore positioned as a moderator of the eco-innovation–circular economy adoption relationship rather than as a general moderator of all relationships in the model. This placement reflects the implementation stage at which in-

novative environmental ideas encounter external constraints, coordination requirements, and resource dependencies [13–18].

Saudi industrial and manufacturing firms provide a theoretically relevant setting for examining this mechanism. These firms operate in resource- and energy-intensive environments in which waste management, emissions reduction, resource efficiency, digital transformation, and circularity have become increasingly important organizational and institutional priorities. At the same time, firms may differ in their ability to absorb institutional initiatives and convert digital and innovative capabilities into implemented circular practices. The Saudi context therefore allows the study to examine the interaction between internal sustainability-oriented capabilities and external enabling conditions within an economy undergoing simultaneous industrial, digital, and sustainability transitions [19,20].

Against this background, the study examines whether green digital technologies are positively associated with sustainable business performance through the sequential roles of eco-innovation and circular economy adoption and whether institutional support strengthens the association between eco-innovation and circular economy adoption. The model integrates the Natural Resource-Based View, Dynamic Capabilities Theory, and Institutional Theory in a staged resource–capability–practice–outcome explanation. The Natural Resource-Based View explains why sustainability-oriented digital resources may possess strategic value; Dynamic Capabilities Theory explains how firms reconfigure these resources through eco-innovation; and Institutional Theory explains how external enabling conditions affect the implementation of circular practices.

This study extends the literature in four respects. First, it moves beyond a direct digitalization–performance explanation by examining a serial conversion mechanism through eco-innovation and circular economy adoption. Second, it distinguishes eco-innovation as an organizational capability from circular economy adoption as an implemented set of practices, thereby avoiding the conceptual conflation of environmental innovation with circular implementation. Third, it identifies institutional support as a boundary condition affecting the transition from environmental innovation to operational circularity. Fourth, it provides evidence from Saudi industrial and manufacturing firms, thereby examining whether the proposed mechanism is relevant within a context characterized by simultaneous digital, industrial, and sustainability transformation. Given the cross-sectional nature of the data, the proposed relationships and empirical findings are interpreted as theoretically ordered associations rather than definitive causal effects.

2. Literature Review and Hypotheses Development

2.1. Theoretical Foundation

This study integrates the Natural Resource-Based View (NRBV), Dynamic Capabilities Theory (DCT), and Institutional Theory to explain how sustainability-oriented digital resources are associated with sustainable business performance through a staged resource–capability–practice–outcome mechanism. Rather than treating the three perspectives as parallel theoretical justifications, the model assigns each theory a distinct explanatory role. The NRBV explains the strategic relevance of green digital technologies, DCT explains the organizational conversion of these technologies into eco-innovation, and Institutional Theory explains the external conditions under which eco-innovation is more effectively embedded in circular economy practices.

The NRBV extends the traditional resource-based view by emphasizing organizational resources and capabilities that support environmentally sustainable strategies and generate longer-term competitive and performance benefits. From this perspective, green digital technologies constitute potentially valuable organizational resources because they can improve environmental visibility, resource tracking, energy management, process

transparency, and sustainability-oriented decision-making. However, the NRBV does not imply that technology ownership alone is sufficient to produce sustainable performance. The strategic value of green digital technologies depends on whether they are directed toward environmental objectives and combined with complementary organizational capabilities. Accordingly, this study treats green digital technologies as sustainability-oriented resources whose performance relevance is realized through subsequent organizational and operational transformation.

DCT explains the next stage of the proposed mechanism. Dynamic capabilities refer to the organizational ability to sense relevant changes, seize emerging opportunities, and reconfigure resources and routines in response to changing conditions. Green digital technologies may enhance the sensing of environmental inefficiencies by generating information on energy use, material flows, emissions, waste, equipment conditions, and supply-chain activities. Nevertheless, information and analytical visibility do not automatically produce redesigned products, cleaner processes, or new sustainability-oriented routines. Eco-innovation represents the reconfiguration capability through which firms transform digital information into environmentally improved products, processes, technologies, and managerial practices. This interpretation positions eco-innovation as an active conversion mechanism rather than as another technological resource.

Circular economy adoption represents a subsequent and conceptually distinct stage. Eco-innovation reflects the organizational ability to develop or improve environmentally oriented solutions, whereas circular economy adoption reflects the actual implementation of practices involving reduction, reuse, recycling, recovery, resource efficiency, lifecycle extension, circular procurement, and closed-loop operations. A firm may develop environmentally oriented ideas and capabilities without fully incorporating them into operational systems. The proposed model therefore distinguishes capability formation from practice implementation. This distinction supports the sequential relationship in which green digital technologies are associated with eco-innovation, eco-innovation is associated with circular economy adoption, and implemented circular practices are associated with sustainable business performance.

Institutional Theory complements the internal resource-and-capability explanation by accounting for the external conditions surrounding implementation. Organizations do not adopt circular practices in isolation. Regulatory arrangements, financial incentives, infrastructure, training, technical assistance, industry collaboration, and institutional clarity can affect the costs, uncertainty, legitimacy, and feasibility of circular implementation. Prior research indicates that environmental policy, institutional quality, industry norms, and supportive arrangements are relevant to eco-innovation and circular behavior [13–16]. Institutional support is therefore conceptualized as an enabling condition that assists firms in converting internally developed eco-innovation into implemented circular practices.

The moderating role of institutional support is positioned specifically on the eco-innovation–circular economy adoption relationship because this relationship captures the transition from organizational capability to operational implementation. The earlier relationship between green digital technologies and eco-innovation primarily concerns the internal use and reconfiguration of organizational resources. By contrast, the implementation of circular economy practices often depends on factors extending beyond the focal firm, including recycling and recovery infrastructure, technical standards, supply-chain coordination, regulatory certainty, funding mechanisms, and access to specialized knowledge. Institutional support is consequently expected to be most relevant at the stage where environmental innovation must be translated into operational and interorganizational practices.

The three theories therefore form a complementary rather than redundant explanation. The NRBV identifies why green digital technologies may constitute strategically relevant sustainability resources. DCT explains how firms convert these resources into eco-innovation capability. Institutional Theory explains why the conversion of eco-innovation into circular economy adoption may vary under different external support conditions. Together, these perspectives produce a resource–capability–practice–condition–outcome framework that supports the study's mediation, serial mediation, and moderation structure.

This integrated reasoning also clarifies the theoretical ordering of the constructs. Green digital technologies constitute the focal resource; eco-innovation represents the organizational conversion capability; circular economy adoption represents implemented operational practice; institutional support represents an external enabling condition; and sustainable business performance represents the multidimensional organizational outcome. The framework does not assume that the stages establish definitive temporal or causal ordering from cross-sectional data. Instead, it tests theoretically ordered associations derived from the combined logic of the three perspectives.

2.2. Green Digital Technologies

Green digital technologies refer to digital applications used for explicit environmental and resource-efficiency objectives. Their value lies not in technological sophistication alone, but in their capacity to improve environmental monitoring, energy management, material traceability, predictive maintenance, waste prevention, lifecycle decisions, and reverse-flow coordination. Depending on the organizational context, such applications may include artificial intelligence, the Internet of Things, big data analytics, blockchain, digital twins, smart monitoring, and automated waste-tracking systems. These technologies are considered green only when their use is linked to verifiable sustainability objectives rather than to general digitalization [6–8].

Research on Industry 4.0 and the circular economy suggests that digital technologies create stronger sustainability value when they are combined with circular manufacturing, eco-innovation, and organizational implementation capabilities [21–23]. Nevertheless, digital–circular performance outcomes vary across firms and contexts because technologies may remain disconnected from environmental routines or operational decision-making [9–11]. Accordingly, the present construct captures the sustainability-directed use of digital technologies, not the firm's overall level of digital maturity.

2.3. Eco-Innovation

Eco-innovation refers to product, process, organizational, and business-model innovation that reduces environmental harm while supporting economic and social value. It may involve recyclable product design, cleaner production, eco-materials, energy-efficient processes, and the integration of environmental criteria into managerial routines. Evidence links eco-innovation to resource-loop closure, although its performance implications vary according to innovation type and organizational context [24–26].

Within the proposed model, eco-innovation represents the capability through which firms convert digital environmental information into redesigned products, processes, and routines. Digital systems can identify inefficiencies, but organizational capabilities are required to interpret this information and act upon it. Recent studies similarly indicate that green technology innovation, green knowledge management, and sustainability-oriented innovation can connect digital capabilities with sustainability outcomes [27–29]. Eco-innovation is therefore treated as a conversion capability rather than as evidence that circular practices have already been implemented.

2.4. Circular Economy Adoption

Circular economy adoption refers to implemented organizational practices through which firms reduce resource consumption, extend product and material lifecycles, reuse inputs, recycle waste, recover value from by-products, and organize closed-loop flows. These practices may include eco-design, circular procurement, reverse logistics, remanufacturing, waste-to-resource processes, product-service systems, and closed-loop supply chains. This implementation focus is important because circular initiatives may create economic, environmental, and social trade-offs at different levels of maturity [30]. Firm-level evidence nevertheless suggests that eco-innovation, lifecycle analysis, redesign, and resource-efficiency practices are positively related to circular implementation and organizational performance [31,32].

In this study, circular economy adoption is treated as a practice-based construct rather than as an environmental intention or policy statement. Firms may declare circular ambitions without integrating circular principles into procurement, production, recovery, reuse, and lifecycle management. The construct therefore focuses on practices embedded in operations, preserving the distinction between eco-innovation as an organizational capability and circular economy adoption as its potential implementation.

2.5. Sustainable Business Performance and Institutional Support

Sustainable business performance is conceptualized in this study as a multidimensional organizational outcome reflected in environmental performance, operational efficiency, overall business performance, organizational reputation, and long-term competitiveness. This operationalization captures how sustainability-oriented practices are associated with both environmental and broader organizational outcomes without assuming that every dimension of the triple bottom line is measured separately.

In the present operationalization, sustainable business performance is reflected through perceived environmental improvement, operational efficiency, overall business performance, organizational reputation, and long-term competitiveness. This narrower operational definition is intentionally distinguished from broader triple-bottom-line conceptualizations that separately measure economic, environmental, and social performance. Circular economy practices may support these organizational outcomes when substantively integrated into operations; however, their benefits may vary according to implementation costs, coordination requirements, and organizational maturity.

Institutional arrangements, financial incentives, infrastructure, regulatory clarity, and collaborative support can influence the feasibility and progression of circular practices [19,33,34].

The inclusion of both constructs is theoretically relevant to the model. Measuring sustainable business performance across environmental and broader organizational outcomes avoids reducing performance to a single environmental indicator while remaining consistent with the five-item instrument used in this study. Institutional support, meanwhile, captures external conditions that may reduce implementation costs and uncertainty. It is therefore expected to strengthen the association between eco-innovation and circular economy adoption rather than directly determine sustainable performance.

2.6. Hypotheses Development

Green digital technologies provide environmental visibility, analytical capacity, and operational information that can support sustainability-oriented innovation. By improving the monitoring of energy, emissions, materials, waste, and process inefficiencies, these technologies expand firms' ability to identify and develop environmentally improved products, processes, and managerial routines. From the NRBV and DCT perspec-

tives, their strategic value is therefore expected to emerge through the development of eco-innovation capability.

H1. *Green digital technologies are positively associated with eco-innovation.*

Green digital technologies may also support circular economy adoption more directly by enabling resource traceability, predictive maintenance, waste monitoring, lifecycle analysis, reverse logistics, and coordination across closed-loop activities. Although technology alone is insufficient to ensure circular implementation, sustainability-oriented digital systems can reduce informational and coordination barriers surrounding circular practices.

H2. *Green digital technologies are positively associated with circular economy adoption.*

Eco-innovation enables firms to redesign products, improve production processes, use environmentally preferable materials, and establish sustainability-oriented managerial routines. These capabilities provide an organizational basis for reducing, reusing, recycling, recovering, and extending the lifecycle of resources. Eco-innovation is therefore expected to precede and support the implementation of circular economy practices rather than being conceptually equivalent to them.

H3. *Eco-innovation is positively associated with circular economy adoption.*

Circular economy adoption can improve resource efficiency, reduce material and waste-related costs, support environmental compliance, and strengthen stakeholder legitimacy. Nevertheless, these outcomes depend on actual operational implementation rather than symbolic sustainability commitments. Consistent with the NRBV, embedded circular practices are expected to be positively associated with environmental and broader organizational performance outcomes.

H4. *Circular economy adoption is positively associated with sustainable business performance.*

Green digital technologies may reveal environmental inefficiencies, but firms require eco-innovation capability to convert this information into redesigned products, processes, and routines. Eco-innovation consequently represents an explanatory mechanism connecting digital resources with circular implementation.

H5. *Eco-innovation mediates the relationship between green digital technologies and circular economy adoption.*

Eco-innovation may generate sustainability-oriented solutions without independently producing broader performance outcomes unless those solutions are embedded in circular operations. Circular economy adoption therefore represents the implementation mechanism through which eco-innovation is associated with sustainable business performance.

H6. *Circular economy adoption mediates the relationship between eco-innovation and sustainable business performance.*

The implementation of circular practices often requires external resources and coordination, including regulatory clarity, financial incentives, technical assistance, infrastructure, training, and institutional collaboration. Institutional support can reduce uncertainty and implementation constraints, thereby making eco-innovation more likely to be incorporated into circular operations.

H7. *Institutional support positively moderates the relationship between eco-innovation and circular economy adoption, such that the relationship is stronger when institutional support is higher.*

The integrated theoretical model proposes that green digital technologies are associated with sustainable business performance through an ordered conversion process. Digital resources support eco-innovation capability; eco-innovation supports circular implementation; and circular implementation is associated with multidimensional performance. This sequence combines the resource logic of the NRBV with the reconfiguration logic of DCT.

H8. *Green digital technologies have a positive indirect association with sustainable business performance through eco-innovation and circular economy adoption in sequence.*

2.7. Conceptual Framework

The conceptual framework positions green digital technologies as sustainability-oriented resources, eco-innovation as a conversion capability, circular economy adoption as implemented practice, and sustainable business performance as the outcome. Institutional support is modeled as an enabling boundary condition because regulations, incentives, infrastructure, technical assistance, and collaboration may reduce implementation uncertainty [35–37]. Figure 1 presents the proposed moderated serial mediation model and the theoretically ordered associations tested in the study.

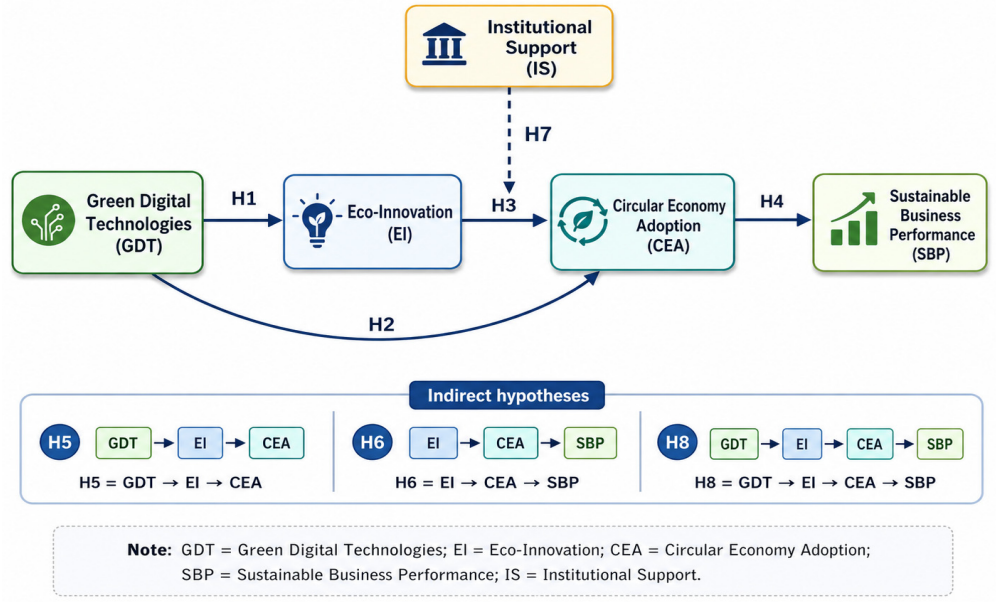


Figure 1. Conceptual Framework. **Note:** H5, H6, and H8 represent indirect pathways formed by the corresponding direct structural relationships.

3. Methodology

3.1. Research Design and Context

This study adopted a quantitative, cross-sectional, explanatory, and variance-oriented design. Partial least squares structural equation modeling (PLS-SEM) was selected because the research objective was to explain variance in key endogenous constructs while estimating a complex model containing multiple latent variables, direct paths, mediation, serial mediation, and moderation. Unlike covariance-based SEM, which primarily emphasizes reproducing the observed covariance matrix and confirming a well-established model, PLS-SEM is appropriate when the analysis emphasizes explained variance and the simultaneous estimation of complex indirect and interaction relationships. Its selection

was therefore based on the study objective and model structure rather than solely on sample size or distributional considerations [38–41].

The empirical setting comprised Saudi industrial and manufacturing firms, where resource intensity, energy use, waste generation, supply-chain complexity, digital transformation, and sustainability requirements make the proposed relationships particularly relevant. The cross-sectional design permits assessment of theoretically specified associations at one point in time but does not establish temporal ordering or causality. Accordingly, the findings are interpreted as associations, while longitudinal research is recommended to test causal direction and changes over time.

3.2. Population, Sample, and Instrument

The target population comprised managers and professionals working in Saudi industrial and manufacturing firms. Purposive sampling was used because the study examines firm-level digital, environmental, innovative, and circular practices that cannot be reliably assessed by respondents without relevant organizational knowledge. Recruitment therefore focused on individuals working in operations, production, sustainability or environmental management, digital transformation, supply-chain management, and quality management. These roles were selected because they provide direct or informed exposure to resource use, environmental monitoring, operational processes, digital systems, and sustainability implementation.

Eligible respondents were expected to work in an industrial or manufacturing firm and to possess sufficient knowledge of at least one of the focal areas examined in the study. Recruitment was directed away from respondents whose roles did not provide a reasonable basis for evaluating organizational digital and sustainability practices. Respondent position and professional experience were subsequently examined to assess informant suitability.

A total of 450 questionnaires were distributed, of which 420 were returned, yielding an overall response rate of 93.3%. Following data-quality screening, 34 returned questionnaires were excluded because of incompleteness, straight-lining, implausibly short completion times, or internally inconsistent response patterns. The final analytical sample therefore comprised 386 usable responses, equivalent to 85.8% of the distributed questionnaires and 91.9% of the returned questionnaires. The retained sample was considered adequate for estimating the proposed PLS-SEM model and its indirect and interaction relationships.

Data were collected using the recovered final administered questionnaire. The instrument contained 25 substantive measurement items. Green digital technologies, eco-innovation, circular economy adoption, sustainable business performance, and institutional support were each measured using five reflective indicators. All items were assessed on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. Table 1 summarizes the operational domains and measurement basis, while Appendix A reproduces the exact administered item wording and the reconstructed item-level provenance audit.

3.3. Questionnaire Development, Pilot Study, and Data Collection

The questionnaire was developed by adapting and synthesizing construct domains reported in prior studies and contextualizing them for Saudi industrial and manufacturing firms. The instrument confirms the exact wording of the 25 substantive measurement items used in the survey. Appendix A reproduces these items and provides a retrospective item-level provenance audit linking each administered indicator to its theoretical source domain and adaptation rationale. Because a contemporaneous item-by-item adaptation log was not maintained during questionnaire development, the provenance audit was re-

constructed retrospectively from the recovered instrument and the cited source literature. This distinction is reported explicitly to preserve transparency. Appendix A reproduces the exact wording of all 25 administered measurement items. In addition, Appendix B shows the Bilingual measurement instrument and back-translation.

Table 1. Construct operationalization and indicative measurement sources.

Construct	Dimensions	Items	Indicative Sources
Green Digital Technologies	Environmental monitoring; resource and energy efficiency; environmental analytics; waste and emissions reduction; sustainability-related operations	5	Adapted and synthesized from [28,42]
Eco-Innovation	Environmental product/service innovation; process improvement; environmentally friendly operational practices; resource-reduction innovation; organizational support for eco-innovation	5	Adapted and synthesized from [16,27,28].
Circular Economy Adoption	Material-waste reduction; reuse and recycling; circular use of materials; lifecycle extension; operational integration of circular principles	5	Adapted and synthesized from [19,28,42]
Sustainable Business Performance	Environmental performance; operational efficiency; overall business performance; organizational reputation; long-term competitiveness	5	Adapted and synthesized from [42,43]
Institutional Support	Government regulation; institutional policies; financial and non-financial incentives; training, guidance, and infrastructure; public and institutional collaboration	5	Developed from institutional-support domains reported by [16,19]

Note: All constructs were measured using a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree.

A pilot study was conducted with 35 members of the target population, whose responses were excluded from the final sample. Participants assessed item clarity, contextual relevance, and questionnaire length. Completion time ranged from 9 to 12 min. Minor wording revisions were made to improve clarity, but no construct was removed. Preliminary Cronbach's alpha values were 0.884 for green digital technologies, 0.861 for eco-innovation, 0.873 for circular economy adoption, 0.901 for sustainable business performance, and 0.856 for institutional support, exceeding the 0.70 guideline.

The final online questionnaire was distributed through professional networks, industry associations, LinkedIn, business directories, and direct organizational contacts. Participation was voluntary and anonymous, and respondents were informed about the study purpose, expected completion time, confidentiality, and academic use of aggregated data.

The questionnaire was translated from English into Arabic and independently back translated into English to assess semantic equivalence, with discrepancies resolved before pilot testing.

3.4. Common Method Bias and Data Analysis

Procedural and statistical measures were used to assess the potential influence of common method bias. Participation was anonymous, item wording was kept neutral, leading questions were avoided, and the measurement sections were separated within the questionnaire. Harman's single-factor test showed that the first unrotated factor accounted for 38.64% of the total variance, below the conventional 50% reference value. In addition, full-collinearity variance inflation factor values ranged from 1.431 to 2.874, remaining be-

low the 3.3 diagnostic threshold. These results provide no indication of severe common method bias; however, they do not eliminate the possibility of residual method variance.

A marker-variable result was not available in the retained analytical records and therefore is not reported. Harman's test and full-collinearity VIFs are consequently treated as diagnostic rather than definitive evidence. The reliance on self-reported, single-respondent, and cross-sectional data remains a methodological limitation.

Data were analyzed using SmartPLS 4. The measurement model was assessed through indicator loadings, Cronbach's alpha, rho_A, composite reliability, average variance extracted, and the heterotrait–monotrait ratio. The structural model was evaluated using collinearity diagnostics, path coefficients, explained variance, effect sizes, Stone–Geisser's Q^2, bootstrapped confidence intervals, mediation, serial mediation, and moderation. A complete PLSpredict assessment was not conducted because item-level prediction errors and the linear-model benchmark were not available in the retained analytical output. Bootstrapping was performed using 5000 resamples. Table 2 shows the criteria.

Table 2. Criteria used to assess measurement and structural models.

Assessment Area	Statistical Indicator	Assessment Guideline
Indicator reliability	Outer loading	Preferably $\geq$ 0.708
Internal consistency	Cronbach's alpha	$\geq$0.70
Internal consistency	Composite reliability	0.70–0.95
Internal consistency	rho_A	$\geq$0.70
Convergent validity	AVE	$\geq$0.50
Discriminant validity	HTMT	<0.85 or <0.90
Collinearity	VIF	Values below 3.3 indicate no critical collinearity concern; values below 5 may remain acceptable depending on context
Structural paths	β, t-value, *p*-value	Bootstrapped confidence interval excludes zero; $p < 0.05$
Explanatory power	R-squared, adjusted R-squared	Higher values indicate stronger explanatory power
Effect size	f-squared	0.02 small, 0.15 medium, 0.35 large
In-sample predictive relevance	Stone–Geisser's Q^2	Values above zero indicate predictive relevance for the endogenous construct within the estimated model
Mediation	Direct and specific indirect effects	Significance assessed using bootstrapped confidence intervals; mediation type determined from direct and indirect effects
Moderation	Latent interaction coefficient and simple slopes	Significance assessed using the bootstrapped interaction coefficient, followed by interpretation of conditional slopes at lower and higher levels of the moderator.

3.5. Ethical Considerations

We respectfully clarify that the present study was conducted independently and was not funded, sponsored, commissioned, or institutionally supported by the University of

Jordan. As such, the manuscript does not fall under the internal ethical approval requirements of the University of Jordan, and approval from its internal ethics committee was not applicable. The authors further confirm that all ethical considerations were observed during the research process. Participation was voluntary, no personally identifiable information was collected, confidentiality and anonymity were ensured, and the collected data were used exclusively for academic research purposes.

In the introduction part of the questionnaire, a consent form was added, including information about the researchers and research institution, research purpose, duration to complete the questionnaire, contact information, and a statement that the agreement is voluntary as below: I have read and understand the provided information and have had the opportunity to ask questions. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and without cost.

4. Data Analysis and Results

4.1. Data Screening and Respondents' Profile

The 386 retained responses were examined to assess respondent suitability before evaluating the structural model. As shown in Table 3, operations managers represented the largest group (24.1%), followed by production managers (18.7%), sustainability or environmental officers (16.3%), digital transformation managers (14.5%), and supply-chain managers (13.2%). The remaining respondents worked in quality management or senior administrative roles.

Table 3. Demographic and organizational profile of respondents (n = 386).

Characteristic	Category	Frequency	Percentage
Position	Operations managers	93	24.1%
	Production managers	72	18.7%
	Sustainability/environmental officers	63	16.3%
	Digital transformation managers	56	14.5%
	Supply chain managers	51	13.2%
	Quality managers	30	7.8%
	Senior administrative staff	21	5.4%
Experience	Less than 3 years	28	7.3%
	3–6 years	119	30.8%
	7–10 years	142	36.8%
	More than 10 years	97	25.1%
Firm size	Medium-sized firms	122	31.6%
	Large firms	264	68.4%

Most respondents possessed substantial professional experience: 36.8% reported 7–10 years and 25.1% reported more than 10 years, meaning that 61.9% had at least seven years of experience. In addition, 68.4% worked in large firms. The concentration of respondents in operational, environmental, digital, supply-chain, and quality-related functions indicates reasonable exposure to the organizational practices examined. Nevertheless, professional position and experience cannot fully eliminate perceptual or single-informant bias.

4.2. Descriptive Statistics and Measurement Model

Descriptive statistics were examined before assessing the measurement and structural models. As shown in Table 4, construct means ranged from 3.55 for institutional support to 3.74 for green digital technologies, indicating moderate-to-high levels across the measured constructs. Institutional support received the lowest mean, suggesting that respondents perceived external enabling arrangements as less developed than the use of sustainability-oriented digital technologies. Standard deviations ranged from 0.69 to 0.78, indicating reasonable variation in responses. Skewness and kurtosis values did not indicate severe distributional irregularities; however, strict multivariate normality was not assumed or required for PLS-SEM estimation.

Table 4. Descriptive statistics for the study constructs.

Construct	Mean	Standard Deviation	Skewness	Kurtosis
Green Digital Technologies	3.74	0.71	−0.436	0.318
Eco-Innovation	3.68	0.76	−0.392	0.274
Circular Economy Adoption	3.61	0.73	−0.287	0.196
Sustainable Business Performance	3.70	0.69	−0.341	0.225
Institutional Support	3.55	0.78	−0.219	0.164

Note: All constructs were measured on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree.

The measurement model was assessed prior to testing the hypotheses to ensure reliability and validity because, according to [40,41], weak measurement can distort the estimates of paths and the interpretation of mediation/moderation. The reflective measurement model was assessed before interpreting the structural relationships. Indicator reliability, internal consistency, convergent validity, and discriminant validity were examined using outer loadings, Cronbach's alpha, rho_A, composite reliability, average variance extracted, and the heterotrait–monotrait ratio. As reported in Table 5, indicator loadings ranged from 0.715 to 0.889. Cronbach's alpha values ranged from 0.881 to 0.929, rho_A values from 0.887 to 0.932, and composite reliability values from 0.913 to 0.941. All values exceeded the recommended minimum of 0.70, while composite reliability values remained below the 0.95 threshold associated with potential indicator redundancy.

Table 5. Reliability and convergent validity assessment.

Construct	Items	Loading Range	Cronbach's Alpha	Rho_A	Composite Reliability	AVE
Green Digital Technologies	5	0.742–0.889	0.902	0.906	0.924	0.670
Eco-Innovation	5	0.731–0.873	0.881	0.887	0.913	0.677
Circular Economy Adoption	5	0.715–0.866	0.895	0.901	0.920	0.657
Sustainable Business Performance	5	0.722–0.884	0.929	0.932	0.941	0.642
Institutional Support	5	0.746–0.871	0.884	0.889	0.915	0.683

Average variance extracted values ranged from 0.642 to 0.683, exceeding the recommended minimum of 0.50 and supporting convergent validity. These results indicate that the indicators explained a sufficient proportion of variance in their respective constructs. They should not, however, be interpreted as independent evidence of content validity, which depends additionally on construct definition, item wording, source attribution, and questionnaire-development procedures.

Discriminant validity was assessed using the heterotrait–Monotrait ratio. Table 6 shows that all HTMT values were below the conservative threshold of 0.85. The highest value was 0.724 between eco-innovation and circular economy adoption. Although the two constructs are theoretically related, this value supports their empirical distinction and is consistent with their conceptualization as capability and implemented practice, respectively [36,44].

Table 6. HTMT results.

Construct	GDT	EI	CEA	SBP	IS
Green Digital Technologies	-				
Eco-Innovation	0.692	-			
Circular Economy Adoption	0.641	0.724	-		
Sustainable Business Performance	0.574	0.652	0.706	-	
Institutional Support	0.481	0.535	0.501	0.469	-

Note: GDT = green digital technologies; EI = eco-innovation; CEA = circular economy adoption; SBP = sustainable business performance; IS = institutional support.

4.3. Structural Model, Mediation, and Moderation

After establishing measurement-model quality, the structural relationships were assessed using bootstrapping with 5000 resamples. Inner variance inflation factor values ranged from 1.386 to 2.642, indicating no critical collinearity concern. Table 7 reports the standardized path coefficients, t-values, and *p*-values.

Table 7. Direct structural relationships and moderation result.

Hypothesis	Path	β	t-Value	*p*-Value	f^2	Effect Magnitude	Decision
H1	GDT -> EI	0.662	18.431	<0.001	0.779	Large	Supported
H2	GDT -> CEA	0.263	5.214	<0.001	0.082	Small	Supported
H3	EI -> CEA	0.487	9.632	<0.001	0.279	Medium	Supported
H4	CEA -> SBP	0.726	22.184	<0.001	1.114	Large	Supported
H7	EI x IS -> CEA	0.118	3.104	0.002	0.025	Small	Supported

Note: Effect-size interpretation follows the conventional reference values of 0.02, 0.15, and 0.35 for small, medium, and large effects, respectively. Effect sizes should be interpreted in conjunction with theoretical relevance and contextual conditions.

Green digital technologies were positively associated with eco-innovation (β = 0.662, $p < 0.001$) and circular economy adoption (β = 0.263, $p < 0.001$), supporting H1 and H2. Eco-innovation was positively associated with circular economy adoption (β = 0.487, $p < 0.001$), supporting H3. Circular economy adoption showed the largest standardized structural coefficient and was positively associated with sustainable business performance (β = 0.726, $p < 0.001$), supporting H4. The interaction between eco-innovation and institutional support was also positive and statistically significant (β = 0.118, $p = 0.002$), supporting H7. The interaction coefficient was comparatively modest and should not be interpreted as evidence of a large practical effect.

Explanatory power was assessed using R^2 and adjusted R^2, while Stone–Geisser's Q^2 was used to examine predictive relevance within the estimated model. As reported in Table 8, green digital technologies explained 43.8% of the variance in eco-innovation. The predictors of circular economy adoption jointly explained 64.1% of its variance, while circular economy adoption explained 52.7% of the variance in sustainable business

performance. All Q^2 values were above zero, indicating predictive relevance within the estimated model.

A complete out-of-sample PLSpredict assessment was not available because the retained analytical output did not include item-level RMSE and MAE statistics or comparisons with a linear-model benchmark. Accordingly, the study does not claim superior out-of-sample predictive performance.

Table 8. Explanatory power and in-sample predictive relevance.

Endogenous Construct	R-Squared	Adjusted R-Squared	Q-Squared
Eco-Innovation	0.438	0.436	0.291
Circular Economy Adoption	0.641	0.637	0.406
Sustainable Business Performance	0.527	0.526	0.331

Note: Q^2 values above zero indicate predictive relevance within the estimated model. They do not constitute a complete assessment of out-of-sample predictive performance.

Specific indirect effects were examined using bootstrapped confidence intervals [27,45]. As shown in Table 9, eco-innovation significantly mediated the relationship between green digital technologies and circular economy adoption (β = 0.322, 95% CI [0.252, 0.400], $p < 0.001$), supporting H5. Because the direct GDT → CEA relationship remained positive and significant, while the direct and indirect coefficients had the same sign, this result indicates complementary partial mediation [28,37]. Circular economy adoption also carried a significant indirect association between eco-innovation and sustainable business performance (β = 0.354, 95% CI [0.278, 0.431], $p < 0.001$), supporting H6. Finally, the serial indirect pathway from green digital technologies to sustainable business performance through eco-innovation and circular economy adoption was significant (β = 0.234, 95% CI [0.173, 0.302], $p < 0.001$), supporting H8. Direct EI → SBP and GDT → SBP paths were not specified in the structural model. H6 and H8 should therefore be interpreted as significant indirect relationships within the proposed model rather than as conclusive evidence of full mediation. Excluding the direct paths prevents a formal distinction between full and partial mediation for these two relationships.

Table 9. Specific indirect and serial indirect relationships.

Hypothesis	Indirect Path	β	t-Value	*p*-Value	95% CI	Decision
H5	GDT -> EI -> CEA	0.322	7.991	<0.001	[0.252, 0.400]	Complementary partial mediation
H6	EI -> CEA -> SBP	0.354	8.774	<0.001	[0.278, 0.431]	Significant indirect relationship
H8	GDT -> EI -> CEA -> SBP	0.234	7.438	<0.001	[0.173, 0.302]	Significant serial indirect relationship

Note: Confidence intervals were obtained through bootstrapping with 5000 resamples. The classification of H5 is based on the significant direct and indirect relationships having the same direction. Direct EI → SBP and GDT → SBP relationships were not estimated.

The significant interaction was examined through conditional slope analysis [16,19]. As shown in Table 10, the relationship between eco-innovation and circular economy adoption was positive under both lower and higher levels of institutional support, but the reported slope was stronger under higher institutional support (β = 0.604) than under lower institutional support (β = 0.365). This pattern is consistent with the proposition that external support facilitates the conversion of eco-innovation into implemented circular practices. Nevertheless, the interaction coefficient itself was small (β = 0.118). The result therefore indicates an incremental enabling role for institutional support rather than a dominant

moderating influence. Statistical significance should not be equated with substantial practical importance. As illustrated in Figure 2, the conditional slopes were interpreted at one standard deviation below and above the mean of institutional support.

The figure presents the reported conditional coefficients for the association between eco-innovation and circular economy adoption under lower and higher institutional support. The intercept was centered for visualization because the original conditional intercepts were not available.

Table 10. Conditional relationship between eco-innovation and circular economy adoption.

Institutional Support Level	Effect of EI on CEA	*p*-Value	Interpretation
Low institutional support	0.365	<0.001	Positive, comparatively weaker relationship
High institutional support	0.604	<0.001	Positive, comparatively stronger relationship

Note: Lower and higher institutional support represent values one standard deviation below and above the mean, respectively. The original SmartPLS interaction-construction settings were not retained and could not be independently verified.

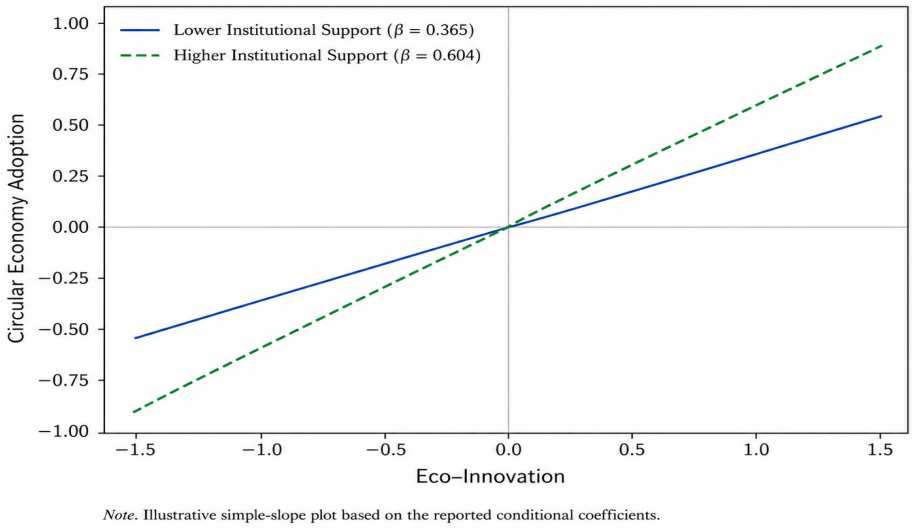


Figure 2. Moderating role of institutional support in the eco-innovation–circular economy adoption relationship.

Table 11 summarizes the hypothesis-testing results. All hypothesized direct, indirect, serial indirect, and moderating relationships were statistically supported. The results are consistent with the proposed sequence linking sustainability-oriented digital resources, eco-innovation capability, circular economy adoption, and sustainable business performance. Given the cross-sectional design, these findings represent theoretically ordered associations rather than confirmed causal or temporal relationships.

Table 11. Summary of hypothesis-testing results.

Hypothesis	Statement	Result
H1	Green digital technologies are positively associated with eco-innovation.	Supported
H2	Green digital technologies are positively associated with circular economy adoption.	Supported
H3	Eco-innovation is positively associated with circular economy adoption.	Supported
H4	Circular economy adoption is positively associated with sustainable business performance.	Supported
H5	Eco-innovation mediates the relationship between green digital technologies and circular economy adoption.	Supported

Table 11. *Cont.*

Hypothesis	Statement	Result
H6	Circular economy adoption carries the indirect relationship between eco-innovation and sustainable business performance.	Supported
H7	Institutional support positively moderates the eco-innovation–circular economy adoption relationship.	Supported
H8	Green digital technologies have a positive serial indirect association with sustainable business performance through eco-innovation and circular economy adoption.	Supported

5. Discussion

This study examined a moderated serial mediation model linking green digital technologies, eco-innovation, circular economy adoption, institutional support, and sustainable business performance. All eight hypotheses were statistically supported. The pattern of coefficients and effect sizes is more consistent with a capability-conversion explanation than with technological determinism. Green digital technologies were strongly associated with eco-innovation, whereas their direct association with circular economy adoption was more limited. Circular economy adoption, in turn, showed the largest direct relationship with sustainable business performance. These findings suggest that digital resources become more relevant to sustainability when they are converted into innovation capabilities and embedded in implemented circular practices.

H1 was supported because green digital technologies were positively associated with eco-innovation ($\beta = 0.662$, $p < 0.001$, $f^2 = 0.779$). The large effect size is consistent with the DCT argument that digital sensing, analytics, connectivity, and environmental monitoring can strengthen firms' ability to identify inefficiencies and reconfigure products, processes, and managerial routines. This interpretation aligns with [27,45], who identify innovation-oriented capabilities, green knowledge management, and green technology innovation as mechanisms connecting digitalization with sustainability outcomes. It is also consistent with [7,8], although prior evidence indicates that results vary across technologies and organizational settings. The present finding should therefore be interpreted at the level of an integrated sustainability-oriented digital capability rather than as evidence that every digital technology contributes equally.

H2 was also supported, but the direct relationship between green digital technologies and circular economy adoption was smaller ($\beta = 0.263$, $p < 0.001$, $f^2 = 0.082$). Digital technologies can improve traceability, maintenance, resource monitoring, lifecycle information, and reverse-flow coordination, supporting the arguments of [1,42], and related Industry 4.0–circular economy research. However, the small effect size indicates that information and connectivity alone are insufficient for substantial circular implementation. Product redesign, supplier participation, investment, recovery infrastructure, and changes in operating models are also required. This interpretation is consistent with studies showing that digital–circular relationships vary among firms and may produce limited or unintended sustainability outcomes when implementation capabilities are weak [10,11,22,46].

H3 was supported through the positive relationship between eco-innovation and circular economy adoption ($\beta = 0.487$, $p < 0.001$, $f^2 = 0.279$). The medium effect size indicates that eco-innovation is an important, but not exclusive, organizational condition for circular implementation. This finding supports the conceptual distinction between eco-innovation as a capability to redesign products, processes, and routines and circular economy adoption as the operational application of reduction, reuse, recycling, recovery, and closed-loop practices. It is consistent with [23,24,28]. Nevertheless, eco-innovation outcomes remain context dependent, and their organizational value may vary according to innovation type, environmental management arrangements, and implementation maturity [25,26].

H4 showed the largest direct relationship in the model. Circular economy adoption was positively associated with sustainable business performance (β = 0.726, $p < 0.001$, $f^2 = 1.114$). This finding is consistent with research linking resource reduction, reuse, recovery, lifecycle management, and circular production with economic, environmental, and social outcomes [31,42,43,47,48]. The result reinforces the argument that sustainability-oriented resources and innovation capabilities are more likely to correspond with performance when converted into implemented operational practices. However, the large coefficient should not be interpreted as evidence that all circular initiatives generate equivalent benefits. Implementation costs, coordination requirements, organizational maturity, and potential sustainability trade-offs may differ across circular practices and firms [30].

The mediation results further clarify the conversion mechanism. H5 was supported because eco-innovation carried a significant indirect relationship between green digital technologies and circular economy adoption (β = 0.322, 95% CI [0.252, 0.400]). Because the direct GDT → CEA relationship also remained significant and had the same direction, the result represents complementary partial mediation. Digital technologies may therefore support circular adoption both through direct informational and coordination functions and indirectly through eco-innovation capability. This finding is consistent with the resource–capability argument advanced by [27,45,49,50].

H6 was supported because circular economy adoption carried a significant indirect relationship between eco-innovation and sustainable business performance (β = 0.354, 95% CI [0.278, 0.431]). The finding indicates that environmentally oriented products, processes, and managerial innovations are more closely associated with multidimensional performance when embedded in procurement, production, recovery, reuse, and lifecycle operations. This interpretation is consistent with [23,24,28]. Because the direct EI → SBP path was not included in the specified model, the result should be described as a significant indirect relationship rather than definitive evidence of full mediation.

H7 was supported by the positive interaction between eco-innovation and institutional support (β = 0.118, $p = 0.002$, $f^2 = 0.025$). The simple slopes indicated that the eco-innovation–circular economy adoption relationship was stronger under higher institutional support (β = 0.604) than under lower support (β = 0.365). This pattern is consistent with Institutional Theory and with evidence that regulation, incentives, technical assistance, infrastructure, knowledge networks, and collaborative arrangements facilitate circular implementation [13,15,16,19,33,34]. Nevertheless, the interaction effect was small. Institutional support should therefore be interpreted as an incremental enabling condition rather than as the primary determinant of circular adoption. Its statistical significance does not imply substantial practical influence in every firm.

H8 supported the serial indirect association between green digital technologies and sustainable business performance through eco-innovation and circular economy adoption (β = 0.234, 95% CI [0.173, 0.302]). This result represents the central integrative contribution of the model. It extends studies that examine digitalization, innovation, circularity, or performance as separate relationships by testing them within one theoretically ordered resource–capability–practice pathway [9,27,28,45]. The contribution lies less in establishing new individual relationships than in clarifying how familiar constructs operate sequentially and under an institutional boundary condition.

R^2 values indicate that the model explained 43.8% of eco-innovation, 64.1% of circular economy adoption, and 52.7% of sustainable business performance. Positive Stone–Geisser Q^2 values indicate predictive relevance within the estimated model. However, out-of-sample predictive performance was not assessed because item-level RMSE and MAE values and the corresponding linear-model benchmark were not available. The findings are also specific to the perceptions of respondents from Saudi industrial and manufacturing

firms. The proposed conversion mechanism may be relevant to other resource-intensive settings, but the coefficient magnitudes and institutional-support relationship should not be generalized without further cross-country and longitudinal evidence.

6. Implications, Conclusion, Limitations, and Future Research

6.1. Theoretical Implications

The study contributes theoretically by integrating the Natural Resource-Based View, Dynamic Capabilities Theory, and Institutional Theory within a resource–capability–practice–condition–outcome framework. The contribution lies not in proposing unfamiliar individual relationships, but in explaining how green digital technologies are associated with sustainable business performance through eco-innovation and circular economy adoption in sequence. It also distinguishes eco-innovation as an organizational conversion capability from circular economy adoption as implemented practice and positions institutional support as a boundary condition at the capability-to-implementation stage. Evidence from Saudi industrial firms further illustrates how internal capabilities and external enabling conditions operate within a transforming institutional context.

6.2. Practical Implications

Managers should prioritize actions according to the reported effect sizes. Because circular economy adoption showed the largest relationship with sustainable business performance, firms should embed resource reduction, recovery, circular procurement, lifecycle extension, and closed-loop routines in operations. Digital investments should support these practices through environmental monitoring, material traceability, waste prevention, and decision support rather than by technology label alone. Resource-constrained firms can begin with applications addressing measurable waste or energy problems, use the information to develop eco-innovation pilots, and scale successful initiatives into broader circular operations. Saudi policymakers can assist through regulatory clarity, incentives, shared recovery infrastructure, technical training, and industry collaboration. Because the moderation effect was small, institutional support should complement rather than replace firms' internal capabilities.

6.3. Conclusions

This study examined the associations among green digital technologies, eco-innovation, circular economy adoption, institutional support, and sustainable business performance in Saudi industrial and manufacturing firms. The PLS-SEM results supported proposed direct, indirect, serial indirect, and moderating relationships. Green digital technologies were strongly associated with eco-innovation but showed a smaller direct association with circular economy adoption. Eco-innovation was positively associated with circular implementation, which had the largest relationship with sustainable business performance. The significant serial indirect relationship supports the proposed resource–capability–practice pathway. Institutional support strengthened the eco-innovation–circular economy adoption relationship, although its effect size was small. Overall, sustainability-oriented digital resources were more closely associated with performance when converted into eco-innovation capability and implemented circular practices. Given the cross-sectional design, the findings represent theoretically ordered associations rather than causal effects.

6.4. Limitations and Future Research

This study has several limitations. First, its cross-sectional design does not establish temporal ordering or causal direction. Reverse causality is possible because firms with

stronger sustainability performance may have greater capacity to invest in green digital technologies and eco-innovation. Longitudinal or panel designs are therefore needed.

Second, all focal variables were reported by single respondents, leaving possible common method variance and perceptual bias despite anonymity and the reported diagnostics. Future studies should use multiple informants, temporal separation, objective indicators, or a theoretically unrelated marker construct.

Third, although the overall response rate could be calculated from the documented distribution and return counts, response-order and timestamp information was not retained. Consequently, an early-versus-late respondent comparison could not be performed, and non-response bias cannot be fully excluded. Future studies should retain response timestamps and contact-wave records to permit formal non-response-bias assessment.

Fourth, the sample was limited to Saudi industrial and manufacturing firms, mainly medium and large organizations. Generalization to small firms, service sectors, or other institutional settings should be cautious. Comparative studies across Gulf Cooperation Council countries and sectors with different resource intensity could test contextual robustness.

Fifth, respondent and firm characteristics were used descriptively rather than as structural controls. Future studies should examine firm size, age, sector, experience, digital maturity, environmental turbulence, leadership commitment, stakeholder pressure, and supply-chain collaboration as controls or boundary conditions. Research could also disaggregate green digital technologies to compare the roles of monitoring, analytics, traceability, and digital twins.

Finally, the study assessed predictive relevance using Stone–Geisser's Q^2 but did not conduct a complete PLSpredict assessment. Item-level RMSE and MAE statistics and comparisons with a linear-model benchmark were not retained. The findings therefore should not be interpreted as evidence of superior out-of-sample predictive performance. Future studies should archive and report the complete PLSpredict output.

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Institutional Review Board Statement: We respectfully clarify that the present study was conducted independently and was not funded, sponsored, commissioned, or institutionally supported by the University of Jordan. As such, the manuscript does not fall under the internal ethical approval requirements of the University of Jordan, and approval from its internal ethics committee was not applicable. The authors further confirm that all ethical considerations were observed during the research process. Participation was voluntary, no personally identifiable information was collected, confidentiality and anonymity were ensured, and the collected data were used exclusively for academic research purposes.

Informed Consent Statement: In the introduction part of the questionnaire, a consent form was added, including information about the researchers and research institution, research purpose, duration to complete the questionnaire, contact information, and a statement that the agreement is voluntary as below: I have read and understand the provided information and have had the opportunity to ask questions. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and without cost.

Data Availability Statement: The data are not publicly available because the participant information and consent process did not provide for public deposition of the dataset. De-identified data may be

made available by the corresponding author upon reasonable request, subject to institutional, ethical, and confidentiality restrictions.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Retrospective Item-Level Provenance and Adaptation Audit

A1. Definition of source codes

- K25: [28]
- SA25: [42]
- AH25: [27]
- DN25: [43]
- AL25: [19]
- Z24: [16]

A2. Modification Reason Codes

- R1: Shift the item to the company level.
- R2: Remove wording specific to transport, tourism, or the country of origin.
- R3: Explicitly link the item to the environmental or circularity objective.
- R4: Condense the scope into a single, clear, and assessable statement.
- R5: Adapt the item for Saudi industrial and manufacturing companies.
- R6: Transform a general concept into an outcome or support perceived by the respondent.

Table A1. Retrospective item-level provenance and adaptation audit of the recovered administered instrument.

Code	Source-Domain Anchor	Final Administered Item	Reason	Source	Decision
GDT1	Environmental-practice monitoring and auditing	Our firm uses digital technologies to monitor environmental performance.	R1, R3, R4, R5	K25; SA25	Retained—administered
GDT2	Technology-supported resource and energy efficiency	Our firm applies digital tools to improve resource and energy efficiency.	R1, R3, R4, R5	K25; SA25	Retained—administered
GDT3	Technology-enabled organizational decision-making	Our firm uses data analytics to support environmentally responsible decisions.	R1, R3, R4, R5	K25	Retained—administered
GDT4	Technology-enabled process and environmental improvement	Our firm adopts smart technologies to reduce waste and emissions.	R1, R2, R3, R4, R5	K25; SA25	Retained—administered
GDT5	Digital technology use in organizational operations	Digital technologies help our firm improve sustainability-related operations.	R1, R2, R3, R4, R5	K25; SA25	Retained—administered
EI1	Introduction of environmentally oriented products/services	Our firm introduces new products or services that reduce environmental impact.	R1, R2, R3, R4, R5	K25; AH25	Retained—administered
EI2	Environmental redesign and process improvement	Our firm improves production processes to minimize environmental harm.	R1, R2, R3, R4, R5	AH25; K25	Retained—administered
EI3	Environmentally oriented innovative practices	Our firm develops environmentally friendly operational practices.	R1, R2, R3, R4, R5	K25; AH25	Retained—administered

Table A1. *Cont.*

Code	Source-Domain Anchor	Final Administered Item	Reason	Source	Decision
EI4	Innovation supporting recycling, reuse, and lower resource consumption	Our firm encourages innovation aimed at reducing resource consumption.	R1, R3, R4, R5	K25; AH25	Retained—administered
EI5	Organizational involvement and support for green innovation	Eco-innovation is actively supported in our firm's sustainability activities.	R1, R3, R5, R6	AH25; Z24	Retained—administered
CEA1	Reduction of material and raw-input use	Our firm adopts practices that reduce material waste.	R1, R2, R3, R4, R5	K25; SA25; AL25	Retained—administered
CEA2	Repeated use and recycling of organizational resources	Our firm reuses or recycles resources whenever possible.	R1, R2, R3, R4, R5	K25; SA25	Retained—administered
CEA3	Use of recycled or substitute materials in organizational processes	Our firm designs processes that support circular use of materials.	R1, R2, R3, R4, R5	K25; SA25	Retained—administered
CEA4	Continued use and lifecycle extension of materials/products	Our firm works to extend the life cycle of resources and products.	R1, R2, R3, R4, R5	K25; AL25	Retained—administered
CEA5	Organizational integration of circular principles	Circular economy principles are integrated into our firm's operations.	R1, R2, R3, R4, R5	K25; AL25	Retained—administered
SBP1	Improvement in environmental performance	Our firm has improved its environmental performance.	R1, R2, R5, R6	DN25; AH25	Retained—administered
SBP2	Operational efficiency, capacity, and waste-related improvement	Our firm has improved operational efficiency through sustainability practices.	R1, R2, R5, R6	SA25; DN25	Retained—administered
SBP3	Improvement in organizational or business performance	Sustainability practices have contributed to better business performance.	R1, R2, R5, R6	DN25	Retained—administered
SBP4	Reputation and market-position improvement	Our firm has strengthened its reputation through sustainable practices.	R1, R2, R5, R6	DN25	Retained—administered
SBP5	Long-term organizational competitiveness	Our firm's sustainability efforts support long-term competitiveness.	R1, R2, R5, R6	DN25	Retained—administered
IS1	Government policies and environmental legal frameworks	Government regulations encourage our firm to adopt sustainable practices.	R1, R2, R3, R4, R5	AL25; Z24	Retained—administered
IS2	Institutional frameworks supporting circular implementation	Institutional policies support the adoption of circular economy practices.	R1, R2, R3, R4, R5	AL25; Z24	Retained—administered
IS3	Financial, economic, and non-financial incentives	Financial or non-financial incentives encourage environmental initiatives.	R1, R2, R3, R4, R5	AL25; Z24	Retained—administered
IS4	Training, technical assistance, guidance, and infrastructure	Training, guidance, or infrastructure support helps our firm implement sustainability practices.	R1, R2, R3, R4, R5	AL25; Z24	Retained—administered
IS5	Government and institutional support networks and collaboration	Collaboration with public or institutional bodies supports our firm's sustainability efforts.	R1, R2, R3, R4, R5	AL25; Z24	Retained—administered

Note: Source-domain anchors summarize the conceptual domain represented in the cited source literature and should not be interpreted as verbatim original item wording unless explicitly indicated. The "Final administered item" column reproduces the wording presented to respondents verbatim. The provenance mapping was reconstructed retrospectively from the recovered questionnaire and the cited literature.

Appendix B. Bilingual Measurement Instrument and Back-Translation

Table A2. Bilingual measurement instrument and back-translation.

Code	Arabic Wording	Back-Translation
GDT1	تستخدم شركتنا التقنيات الرقمية لمراقبة الأداء البيئي.	Our firm uses digital technologies to monitor environmental performance.
GDT2	تطبق شركتنا أدوات رقمية لتحسين كفاءة استخدام الموارد والطاقة.	Our firm applies digital tools to improve resource and energy efficiency.
GDT3	تستخدم شركتنا تحليلات البيانات لدعم القرارات المسؤولة بيئيًا.	Our firm uses data analytics to support environmentally responsible decisions.
GDT4	تتبنى شركتنا تقنيات ذكية للحد من النفايات والانبعاثات.	Our firm adopts smart technologies to reduce waste and emissions.
GDT5	تساعد التقنيات الرقمية شركتنا على تحسين العمليات المرتبطة بالاستدامة.	Digital technologies help our firm improve sustainability-related operations.
EI1	تقدم شركتنا منتجات أو خدمات جديدة تقلل الأثر البيئي.	Our firm introduces new products or services that reduce environmental impact.
EI2	تحسّن شركتنا عمليات الإنتاج للحد من الضرر البيئي.	Our firm improves production processes to minimize environmental harm.
EI3	تطوّر شركتنا ممارسات تشغيلية صديقة للبيئة.	Our firm develops environmentally friendly operational practices.
EI4	تشجع شركتنا الابتكار الهادف إلى خفض استهلاك الموارد.	Our firm encourages innovation aimed at reducing resource consumption.
EI5	يُدعَم الابتكار البيئي بفاعلية ضمن أنشطة الاستدامة في شركتنا.	Eco-innovation is actively supported in our firm's sustainability activities.
CEA1	تتبنى شركتنا ممارسات تقلل هدر المواد.	Our firm adopts practices that reduce material waste.
CEA2	تعيد شركتنا استخدام الموارد أو تدويرها كلما كان ذلك ممكنًا.	Our firm reuses or recycles resources whenever possible.
CEA3	تصمم شركتنا عمليات تدعم الاستخدام الدائري للمواد.	Our firm designs processes that support circular use of materials.
CEA4	تعمل شركتنا على إطالة دورة حياة الموارد والمنتجات.	Our firm works to extend the life cycle of resources and products.
CEA5	تدمج شركتنا مبادئ الاقتصاد الدائري في عملياتها.	Circular economy principles are integrated into our firm's operations.
SBP1	حققت شركتنا تحسنًا في أدائها البيئي.	Our firm has improved its environmental performance.
SBP2	حسّنت شركتنا كفاءتها التشغيلية من خلال ممارسات الاستدامة.	Our firm has improved operational efficiency through sustainability practices.
SBP3	أسهمت ممارسات الاستدامة في تحسين أداء أعمال شركتنا.	Sustainability practices have contributed to better business performance.
SBP4	عززت شركتنا سمعتها من خلال الممارسات المستدامة.	Our firm has strengthened its reputation through sustainable practices.
SBP5	تدعم جهود الاستدامة في شركتنا القدرة التنافسية طويلة الأجل.	Our firm's sustainability efforts support long-term competitiveness.
IS1	تشجع اللوائح الحكومية شركتنا على تبني الممارسات المستدامة.	Government regulations encourage our firm to adopt sustainable practices.
IS2	تدعم السياسات المؤسسية تبني ممارسات الاقتصاد الدائري.	Institutional policies support the adoption of circular economy practices.
IS3	تشجع الحوافز المالية أو غير المالية المبادرات البيئية.	Financial or non-financial incentives encourage environmental initiatives.
IS4	يساعد التدريب أو الإرشاد أو دعم البنية التحتية شركتنا على تنفيذ ممارسات الاستدامة.	Training, guidance, or infrastructure support helps our firm implement sustainability practices.
IS5	يدعم التعاون مع الجهات العامة أو المؤسسية جهود الاستدامة في شركتنا.	Collaboration with public or institutional bodies supports our firm's sustainability efforts.

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