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How Big Data Analytics Capability Promotes Green Radical Innovation? The Effect of Corporate Environment Ethics in Digital Era

Weiwei Wu, Xue Li * and Guowei Ruan

Business School, Harbin Institute of Technology, West Dazhi Street 92, Nangang District, Harbin 150001, China; wuweiwei@hit.edu.cn (W.W.); ruanguowei1@126.com (G.R.)
* Correspondence: 20b910050@stu.hit.edu.cn; Tel.: +86-17862703192

Abstract: In the digital economy era, firms pursue innovation while also considering their environmental impact to ensure alignment with sustainability. However, existing research offers limited insights into how corporate environmental ethics influence the relationship between big data analytics capabilities (BDACs) and green radical innovation (GRI). This study investigates the impact of BDACs, environmental ethics, and GRI, using a sample of 291 firms and integrating resource-based theory with an environmental ethics perspective. Empirical results indicate that environmental ethics positively moderate the positive relationships between the three dimensions of BDAC—managerial, technical, and talent capability—and GRI. Moreover, there are differences in the moderating effects on this relationship. This study enriches boundary condition research on how BDACs impact GRI. Additionally, it contributes to understanding the mechanisms through which environmental ethics affect GRI, highlighting the combined effect of environmental ethics and BDAC. Furthermore, this study advances research on the heterogeneous role of environmental ethics, emphasizing the importance of enhancing corporate environmental ethics in transforming BDA technical capability into GRI. This contribution offers a new perspective on how firms can more effectively leverage their BDAC toward sustainable development.

Keywords: big data analytics capability; environmental ethics; green radical innovation

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Academic Editor: Sitalakshmi Venkatraman

Received: 1 April 2025
Revised: 7 May 2025
Accepted: 9 May 2025
Published: 12 May 2025

Citation: Wu, W.; Li, X.; Ruan, G. How Big Data Analytics Capability Promotes Green Radical Innovation? The Effect of Corporate Environment Ethics in Digital Era. *Systems* **2025**, *13*, 370. https://doi.org/10.3390/systems13050370

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

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1. Introduction

Radical innovation (RI) is a crucial paradigm for businesses. It focuses on creating radical new products, services, and technologies, among others, and helps firms achieve rapid advancements and gain competitive edges [1,2]. In today's world, where modernization aims for harmony between humans and nature, green radical innovation (GRI) becomes essential [3]. It effectively addresses pressing issues like environmental pollution and resource depletion, playing a vital role in sustainable development [4]. GRI involves firms breaking away from existing inherent traditional paths to develop eco-friendly innovation [5]. As a cornerstone for comprehensive green transformation, GRI expands the technological boundaries of firms that are lagging behind. It drives their research and development efforts toward the cutting edge of innovation. This approach infuses new energy into enhancing firms' green transformation and boosting their competitive advantages [2,6,7]. However, high levels of innovation often entail greater risks, meaning achieving success in GRI is challenging due to the inherent risks that may cause a firm to resist change [8,9]. Thus, this study explores how to reduce the risks and uncertainties faced by firms in GRI.

Big data analytics (BDA) is widely recognized for its capability to reduce the risks and uncertainties encountered by firm [10,11]. Big data analytics capability (BDAC) can effectively help enterprises transform vast and complex big data into useful knowledge, thereby serving innovation and helping firms gain competitive advantages [3,9]. Based on the resource-based theory, BDAC is grounded in the principles of resource heterogeneity, immobility, and inimitability. It emphasizes the significance of strategic alignment in effectively utilizing these resources to drive superior innovation within firms [12]. Previous studies have extensively explored the relationship between BDACs and different firm innovations, including business model innovation [13], social innovation [14], supply chain innovation [15], sustainable innovation [16], green innovation [17,18], radical innovation [9], and ambidextrous innovation [19]. Most studies suggest that the former has a positive impact on the latter, but some argue that the direct impact is not significant [20,21]. Scholars have identified key moderating factors in these relationships, such as environmental uncertainty [22], technology uncertainty [15], industry type, and firm size [23].

Despite the arguments suggesting that BDAC plays a crucial role in innovation, research on the impact of BDAC on GRI has not been thoroughly explored. Some researchers emphasize the role of different dimensions of BDAC and highlight the importance of studying the mechanisms of BDAC in more granular classifications to better reveal its underlying mechanism [12,24]. However, the impact of different types of BDACs on GRI remains unclear, and research on their mechanisms is particularly lacking. Therefore, this study proposes question 1:

Q1: How do the different dimensions of BDAC influence GRI?

Given the high-risk nature and extended return cycles associated with GRI [5], firms with strong BDAC may still be inclined to allocate resources to non-GRI activities due to profit-driven motives. The environmental ethics perspective offers a new research approach to this issue. The growing importance of environmental concerns has driven environmental ethics into corporate strategic decision-making [25]. Based on this perspective, firms that adhere to environmental ethics are better equipped to recognize and proactively respond to institutional pressures [26,27], thereby allocating resources toward GRI. Therefore, it is necessary to integrate BDACs with corporate environmental ethics to investigate how their combined influence contributes to GRI. Environmental ethics also stress that in the pursuit of innovation, firms must be mindful of their environmental impact to ensure their actions are aligned with sustainable development principles [27]. In this context, the role of environmental ethics is gaining increasing importance. Environmental ethics assert that firms should not solely focus on economic benefits during the innovation process but also consider the environmental consequences of their activities, ensuring they do not cause irreversible damage to ecosystems. Federica (2020) pointed out that the data revolution has led to environmental problems that threaten sustainable development [28]. Big data has a large footprint, often requiring non-renewable energy. The impact of the data revolution on sustainable development is well recognized, particularly through the high consumption of non-renewable energy and the significant emissions of carbon dioxide and other pollutants associated with big data centers and cloud computing—key components of BDAC.

Although some studies have focused on the relationship between big data and environmental sustainability, such as using big data technologies to achieve environmental sustainability [24] and the "greening" of big data ecosystems [29], the role of environmental ethics in the relationship between BDAC and GRI has not been adequately addressed. This limitation hinders the understanding of how firms in the digital era balance value creation with environmental considerations. Consequently, it may lead to the neglect of environmental ethics in data governance processes. This neglect can affect the effectiveness of data governance mechanisms and cause a misalignment between data initiatives and

environmental policies or sustainable development goals [30–32]. Based on this, this study proposes research question 2:

Q2: How does environmental ethics moderate the relationship between different dimensions of BDAC and GRI?

Therefore, this study aims to investigate the impact of BDAC on GRI from a more granular perspective. Akter (2016) [12] categorized BDAC into three dimensions: management, technology, and talent. Big data analytics management capability (BDAMC) is reflected in the frameworks that assist firms in making informed decisions. Through effective big data management, firms can adopt suitable management frameworks that facilitate accurate decision-making. Big data analytics technology capability (BDATEC) refers to the flexibility of BDA systems, enabling firms to quickly develop, deploy, and utilize various resources. Big data analytics talent capability (BDATAC) involves the ability of analysts to mine and predict data, thereby supporting firms in making well-informed decisions. Specifically, this study examines how the three dimensions of BDAC—BDAMC, BDATEC, and BDATAC—influence GRI and how environmental ethics may moderate these relationships.

This study contributes to the research on the mechanisms by which BDACs impact firm innovation. From the perspective of BDAC, the impact of different BDACs on GRI is explored at a more granular level, with environmental ethics introduced as a boundary condition, thereby enriching the fine-grained research on BDAC and the boundary condition research. Furthermore, this study contributes to the research on the mechanisms by which environmental ethics impact innovation. By investigating how environmental ethics may shape the relationship between BDAC and GRI, a novel perspective on the role of ethics in data-driven innovation is provided. Considering environmental ethics as a moderating factor opens new research avenues related to ethical considerations in data governance mechanisms. Additionally, this study further contributes to the research on the heterogeneity of the role of environmental ethics by comparing the differences in the moderating effects of environmental ethics on various BDAC and GRI relationships. The remaining sections of this research are organized as follows: Section 2 provides the theoretical background and hypotheses; Sections 3 and 4 provide the research design and results; and the final section summarizes the findings and implications of this study.

2. Theoretical Background and Hypothesis

The resource-based theory posits that a firm's sustainable competitive advantage stems from its possession of heterogeneous, imperfectly imitable, and non-substitutable strategic resources [33]. These resources encompass human capital, technological assets, and managerial competencies, which collectively enable firms to create unique competitive advantages. The theory emphasizes that resource heterogeneity leads to differential resource endowments among firms, while the imperfect imitability and non-substitutability of these resources ensure that such advantages cannot be easily replicated by competitors or acquired through market transactions [11]. Building upon this theoretical foundation, firms can achieve sustained innovation in dynamic competitive environments by effectively integrating and leveraging their distinctive resource portfolios. The inherent characteristics of BDAC align closely with the core tenets of resource-based theory, as they collectively create barriers to imitation and substitution that are essential for sustaining competitive advantage in sustainability-oriented innovation contexts [34]. BDAC facilitates the formation of unique green knowledge repositories through the efficient mining and integration of internal and external environmental data. This capability enables firms to transcend path dependencies associated with conventional environmental technologies and catalyze breakthrough green solutions.

2.1. Big Data Analytics Capabilities (BDACs) and Green Radical Innovation (GRI)

2.1.1. Big Data Analytics Management Capability (BDAMC) and GRI

BDAMC is primarily reflected in the frameworks that assist firms in making informed decisions. Through effective big data management, firms can ensure the adoption of appropriate management frameworks for accurate decision-making. BDAMC is manifested in four key aspects: planning, investment, coordination, and control [35,36].

From a planning perspective, the utilization of BDAMC aids in identifying business opportunities, enabling firms to better understand market demands, consumer concerns, and competitor dynamics. This insight provides a more accurate scientific basis for decision-making, helping to reduce the risks associated with GRI, which is characterized by high risk levels, environmental friendliness, and disruptiveness. By efficiently focusing on potential market opportunities and industry trends, firms can better promote GRI [9,37,38].

From an investment perspective, if firms cannot effectively manage investments in big data, complex and redundant data cannot be converted into firm value. BDAMC bridges the gap between big data and the conversion of firm value, transforming big data into a foundational source for GRI and achieving value conversion. This transformation is crucial for environmentally friendly innovations, which require significant resource allocation and strategic investment [39,40].

From a coordination perspective, the enhancement of BDAMC facilitates collaboration among various resources and stakeholders in the innovation process. This collaboration is essential for GRI, as it often involves integrating diverse expertise and ensuring alignment towards disruptive and sustainable goals [41].

Finally, from a control perspective, the accurate evaluation of big data solutions, the clear delineation of responsibilities for big data analysts, the diligent tracking and monitoring of these analysts by firms, and performance-based rewards bolster risk management and optimization throughout the GRI process [42]. This leads to positive feedback loops and positively impacts GRI with high-risk, environmentally friendly, and disruptive innovation [42].

Based on these insights, the study proposes the following hypothesis:

H1: *There is a positive relationship between BDAMC and GRI.*

2.1.2. Big Data Analytics Technology Capability (BDATEC) and GRI

BDATEC refers to the flexibility of BDA systems in swiftly developing, deploying, and utilizing diverse resources. Connectivity, compatibility, and modularity are the core aspects of BDATEC. In response to environmental and market uncertainties, firms are required to integrate resources within their innovation strategies [12].

Flexible BDATEC enables firms to connect distributed data, establish data channels, ensure compatibility, and foster innovation through the development of novel models or the deployment of new software [15]. In the context of GRI, characterized by environmental friendliness, high risk, and disruptiveness, strong BDATEC is crucial. GRI involves more pronounced coordination challenges than other business activities. It encompasses not only the integration of both the green and innovation aspects but also the convergence of disruptive innovation. This frequently implies heightened risks and substantially increased complexity in resource allocation and decision-making processes. Strong BDATECs enable firms to acquire and analyze diverse data from various functional units, allowing them to integrate different needs and guide environmentally friendly and disruptive innovation [43]. Thus, BDATEC plays a key role in addressing the complex coordination demands of GRI, helping firms manage the high-risk and complex innovation processes more effectively.

Furthermore, the stronger the BDATEC, the better it supports firms in synchronizing and merging overlapping data, repairing lost information, and maintaining continuous information flow for real-time decision-making. This enhances compatibility and facilitates innovative collaboration and rapid analysis, which are crucial for the high-risk and disruptive nature of GRI.

Finally, the stronger the BDATEC, the better it supports the reorganization of different data modules. This flexibility encourages firms to reconfigure during model development, helping to identify business opportunities that align with sustainable goals and enhancing effective innovation. By leveraging BDATEC, firms can pursue green radical innovations more effectively, which are environmentally friendly and capable of transforming markets [44,45].

Based on this, this study proposes the following hypothesis:

H2: *There is a positive relationship between BDATEC and GRI.*

2.1.3. Big Data Analytics Talent Capability (BDATAC) and GRI

BDATAC refers to the ability of analysts to mine and predict data to support firms in making correct decisions. It is characterized by the acquisition of technical knowledge, technical management knowledge, business knowledge, and relational knowledge, all of which are crucial for ensuring and enhancing innovation performance [12,46]. BDATAC encompasses technical knowledge, technical management knowledge, business knowledge, and relational knowledge, all of which are crucial in facilitating this innovative process.

Firstly, technical knowledge and technical management knowledge establish a solid foundation for firms to conduct BDA. These competencies include specialized skills such as database management and big data visualization, enabling firms to maintain and optimize existing decision models while driving technological advancements in green innovation. This capability is essential for identifying and developing green products and services with substantial innovation potential [47,48], thereby reducing trial-and-error costs and increasing the success rate of GRI.

Secondly, enhanced business knowledge enables BDA to more effectively comprehend and navigate the strategic development environment. In the face of environmental uncertainty, they can employ decision models to predict future trends, assisting firms in identifying GRI directions that align with their long-term development strategies [49,50]. This ability is particularly critical in GRI, where balancing sustainability with market demands is paramount.

Furthermore, relational knowledge enables BDA to communicate and coordinate effectively across departments and with clients. This proficiency allows firms to make more accurate assessments of market potential and consumer demands, thereby reducing operational costs and market risks associated with GRI activities and enhancing innovation efficiency [51]. Through comprehensive mining and analyzing data, BDATAC can reveal hidden patterns and trends, providing strategic insights and recommendations for GRI development [52,53]. This not only supports firms in achieving success in environmentally friendly and high-risk innovation projects but also helps maintain a competitive edge in disruptive innovation. Such capabilities ensure that firms can pursue sustainable development while achieving the objectives of GRI [54].

Based on this, this study proposes the following hypothesis:

H3: *There is a positive relationship between BDATAC and GRI.*

2.2. The Moderating Effect of Environment Ethics

Environmental ethics refer to a firm's environmental responsibilities, visions, and actions during production processes. This includes having clear and specific environmental policies. It also involves considerations for environmental investments or procurement in budgeting. Additionally, it encompasses the extent to which the firm integrates its environmental planning, vision, or mission into its marketing activities and firm culture [55,56].

2.2.1. The Moderating Effect of Environmental Ethics on the Relationship Between Big Data Analytics Management Capability (BDAMC) and GRI

The higher the degree of firm environmental ethics, the more likely it is to incorporate environmental protection elements into strategic planning [25,57]. Such planning of BDAMC often aims to identify and seize business opportunities. By clearly defining these plans, firms can build effective BDA models for analysis. A strong sense of environmental ethical responsibility signifies that the firm prioritizes environmental protection as a key strategic objective [58], guiding the continuous refinement of BDA plans to uncover green and sustainable innovation opportunities that align with corporate strategies.

In practice, enhancing environmental ethical responsibility enables firms to better align ecological balance with business goals [25,59]. This integration is also reflected in investment decisions using BDAMC, where firms guided by strong environmental ethics are more inclined to develop products emphasizing energy efficiency, environmental protection, and health benefits. Such investments not only promote the development of green innovations but may also lead to the creation of entirely new eco-friendly brands [60].

Furthermore, as the culture of environmental ethics strengthens, it reduces the barriers to cross-functional synchronization within firms [55]. A cohesive organizational culture can foster better alignment across operations, consumer needs, and supply chain management [61]. In such an environment, BDA can more effectively coordinate with diverse stakeholders, bridging gaps between business objectives, data analytics, and IT. This improved coordination ensures a smoother integration of BDAMC with the promotion of GRI.

In summary, corporate environmental ethics play a critical role in enhancing the planning, investment, coordination, and control processes that link BDAMC to GRI. Therefore, environmental ethics further amplify the positive effects of BDAMC on GRI, reinforcing the firm's capacity to undertake high-risk, environmentally friendly, and disruptive innovations.

Based on this, the following hypothesis is proposed:

H4: *Corporate environmental ethics will positively moderate the positive relationship between BDAMC and GRI.*

2.2.2. The Moderating Effect of Environmental Ethics on the Relationship Between Big Data Analytics Technology Capability (BDATEC) and GRI

BDATEC influences GRI by enhancing the flexibility of big data platforms, such as enabling cross-functional data connections, multi-platform data compatibility, and modular model construction [35].

When a firm fulfills environmental ethical responsibilities, it is more likely to gain recognition from the government and other stakeholders, thereby obtaining more advantageous resources and collaborations [57,62]. BDATEC can continuously leverage these resources to enhance platform flexibility and achieve a higher degree of cross-functional data connections and multi-platform compatibility, thereby promoting improved GRI outcomes.

Furthermore, when the level of environmental ethics is high, firms are more likely to consider the environmental impact of their decisions when utilizing relevant technologies

for analysis [63,64]. Clearly, a firm's focus on environmental ethical responsibilities provides new constraints for big data decision-making, with higher corporate environmental ethics indicating greater importance placed on environmental protection strategies [58,65]. Thus, when firms employ BDA technologies for innovation decisions, they directly filter out data flows that do not align with their strategic objectives, simplifying the complex data cleaning process and making GRI decisions more efficient. During the model-building process, this new constraint is incorporated into the innovation model, making corporate innovation more directive, guiding the direction of GRI, and enabling firms to undertake targeted R&D that meets market needs and achieves sustainable development [66,67]. In summary, the higher the level of corporate environmental ethics, the more pronounced the impact of BDATEC on GRI.

Based on this, we propose the following hypothesis:

H5: *Corporate environmental ethics will positively moderate the positive relationship between BDATEC and GRI.*

2.2.3. The Moderating Effect of Environmental Ethics on the Relationship Between Big Data Analytics Talent Capability (BDATAC) and GRI

BDATAC influences GRI through the mastery of technical knowledge, technical management knowledge, business knowledge, and relational knowledge [42,68]. The higher the corporate environmental ethics, the more it stimulates the accumulation of knowledge and skills related to green innovation among BDA talent [69]. These skills must align with big data technical knowledge and technical management knowledge, facilitating the construction of decision-making models that support sustainable development and the identification of hidden market opportunities for GRI [27].

Furthermore, higher corporate environmental ethics foster a strong internal culture of environmental protection and ecological balance [70]. This enables BDA talent to gain a deeper understanding of the firm's culture from a business knowledge perspective, enhancing their grasp of environmental strategies and practices. This cultural alignment creates cognitive barriers against competitors, as firms with high environmental ethics are better positioned to develop proprietary green technologies and processes [62]. This understanding helps establish cognitive barriers against competitors, promoting GRI and the introduction of innovative, eco-friendly products that are difficult for competitors to imitate [3].

Moreover, when corporate environmental ethics are high, employees' pride and sense of belonging to the firm are significantly enhanced, which boosts their initiative and enthusiasm [30]. This heightened motivation translates into improved relational capabilities, as employees are more willing to engage in cross-functional collaboration and knowledge sharing [59]. This improvement in relational capabilities allows BDA talent to collaborate more effectively, advancing the internal collaborative innovation capabilities necessary for GRI [71]. In summary, the higher the level of corporate environmental ethics, the more pronounced the impact of BDATAC on GRI.

Based on this, the following hypothesis is proposed:

H6: *Corporate environmental ethics will positively moderate the positive relationship between BDATAC and GRI.*

The conceptual model is illustrated in Figure 1.

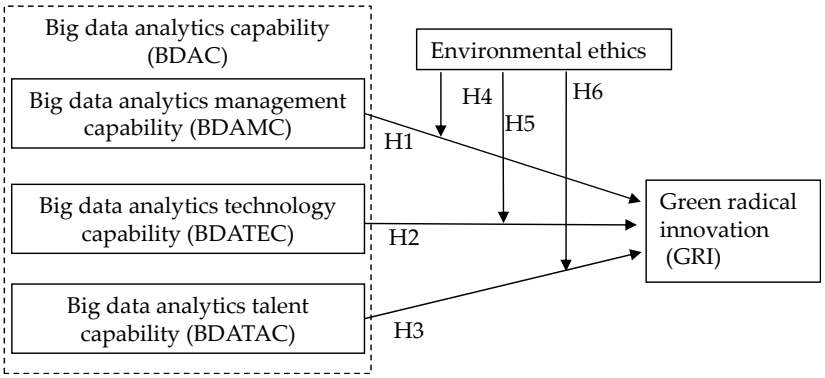


Figure 1. Conceptual model.

3. Methods

3.1. Research Setting and Data Collection

This study employs questionnaire survey methodology for data collection in Chinese firms. Given the research objectives, it was crucial for respondents to have a comprehensive understanding of GRI, BDAC, and other relevant aspects of firm operations. Therefore, middle and senior management within these firms were selected as survey questionnaire respondents to enhance the objectivity and reliability of the data collected. The distribution and retrieval of questionnaires were conducted through three primary channels: First, questionnaires were to administered to MBA students who hold management positions within firms, with immediate on-site collection. Second, the research team leveraged their social networks to disseminate questionnaires via email to corporate managers. Third, field surveys were conducted by consulting firm directories, and the team conducted stratified sampling based on the proportion of the total number of firms in different regions, enabling questionnaire distribution across various regions nationwide.

Data collection took place from October 2023 to March 2024. Through these three channels, a total of 600 initial questionnaires were distributed (Channel 1: 150; Channel 2: 150; Channel 3: 300). The number of returned questionnaires was 348 (Channel 1: 135; Channel 2: 98; Channel 3: 115). After excluding incomplete responses and those with logical inconsistencies, the number of valid responses obtained was 291 (Channel 1: 121; Channel 2: 84; Channel 3: 86). This resulted in an effective response rate of 83.6%. This response rate adequately meets the requirements for empirical data analysis. The respondents' distribution characteristics are presented in Table 1.

In accordance with the ethical guidelines of our school and the Declaration of Helsinki, this study is exempt from requiring ethical approval, ensuring participant anonymity and avoiding sensitive topics. Informed consent was obtained from all subjects and/or their legal guardians at the time of data collection, clearly explaining the study's purpose, data usage, and potential risks while stressing the voluntary nature of participation. This approach underscores our dedication to ethical standards, prioritizing the rights and welfare of participants. As the study is exempt and does not involve procedures necessitating institutional review board approval, no specific ethical approval number was issued.

Table 1. Sample distribution characteristics.

Variable	Category	Frequency	Percentage (%)
Respondent Position	Chairman/general manager and executives	65	22.34
	Department manager	73	25.09
	Big data business supervisor	153	52.58
Firm Age	Less than 1 year	2	0.69
	1–5 years	27	9.28
	5–10 years	63	21.65
	10–15 years	59	20.27
	More than 15 years	140	48.11
Firm Size	300 employees or less	138	47.42
	301–1000 employees	42	14.43
	1001–2000 employees	35	12.03
	2001–5000 employees	28	9.62
	More than 500 employees	48	16.49
Firm Nature	Sino-foreign joint venture enterprises	53	18.21
	State-owned and collective enterprises	98	33.68
	Foreign enterprises	8	2.75
	Private enterprises	132	45.36
Firm Geographic Location	Eastern region	184	63.23
	Central region	51	17.53
	Western region	56	19.24

3.2. Measurement Scales

The measurement scales were primarily adapted from previous studies. The questionnaire used in this study is very mature and has been fully utilized by scholars from different research regions. Before the official launch of the questionnaire, this study polished it and invited experts to evaluate it in order to better capture the information needed for the research.

Dependent variable: GRI was operationalized based on the measurement framework proposed by Al-Khatib et al. (2022) [3] and Lenderink et al. (2022), [5] incorporating 5 items.

Independent variables: The constructs of BDAMC, BDATEC, and BDATAC were adapted from established scales developed by Akter et al. (2016) [12] and Wu et al. (2024) [9]. These constructs comprise 16, 12, and 16 measurement items, respectively.

Moderating variable: Environmental ethics was measured using a scale aligned with the works of Chang et al. (2011) [55] and Song et al. (2024) [59], consisting of 4 items.

Control Variables: Referring to previous research [9,72], some variables were controlled to ensure the stability of the research findings. Several control variables were included as follows: firm size, firm nature, firm age, firm research and development (R&D) intensity, high-tech type (coded as 1 for high-tech firms and 0 otherwise), and industry type.

The items in the questionnaire were crafted using a five-point Likert scale to assess participants' responses, where one indicates strong disagreement and five indicates strong agreement.

3.3. Validity and Reliability Testing

This study employs confirmatory factor analysis to assess validity. The factor loadings of each variable item range from 0.504 to 0.962 (see Table 2), all exceeding the threshold value of 0.500. The average variance extracted (AVE) values are all greater than 0.600. The composite reliability (CR) values are all above 0.900 (see Table 3), indicating that the validity of the questionnaire is good. This study utilizes Cronbach's Alpha for reliability testing, all exceeding the threshold value of 0.700, indicating that the reliability of the

questionnaire is good (see Table 3). The discriminant validity of the five-factor model in this study was examined through structural equation modeling (SEM). The measurement model demonstrated good fit with the data: $x^2/df = 1.41$, RMSEA = 0.037, SRMR = 0.042, CFI = 0.912, and TLI = 0.907, all exceeding conventional criteria for model acceptability. In addition, in Table 4, four alternative models were set, and the fitting indicators of each alternative model were not better than those of the five-factor model. From this, it can be seen that the five-factor model has good discriminant validity. The validity and reliability of the scales used meet the requirements.

Table 2. Measurement items of key variables.

Variable	Items	Loadings
BDAMC [9,12]	1. Our firm strategically uses big data analytics to identify innovation opportunities.	0.857
	2. Our firm has made adequate preparations to utilize and introduce big data analytics capabilities.	0.535
	3. Our firm formalizes and systematizes the big data analytics planning process.	0.812
	4. Our firm frequently adjusts its big data analytics plans to better adapt to changes.	0.507
	5. When making investment decisions in big data analytics, our firm considers and estimates its impact on employee productivity.	0.825
	6. When making investment decisions in big data analytics, our firm considers and predicts whether these investments will significantly enhance user decision-making efficiency.	0.818
	7. When making investment decisions in big data analytics, our firm estimates the additional training costs incurred by users due to this decision.	0.860
	8. When making investment decisions in big data analytics, our firm predicts how much time managers will need to supervise this change.	0.598
	9. Business analysts and frontline employees frequently meet formally and informally to discuss important issues.	0.819
	10. Business analysts and frontline employees often participate in cross-functional meetings.	0.892
	11. Analysts and frontline staff can work harmoniously together.	0.901
	12. Consensus is reached between business analysts and frontline personnel, facilitating the sharing of ideas for managers and executors to utilize available knowledge.	0.883
	13. In our firm, responsibilities for the development of big data analytics are clearly defined.	0.907
	14. Our firm is confident in the appropriate evaluation of big data analytics project proposals.	0.911
	15. Our firm continuously monitors the effectiveness of its big data analytics capabilities.	0.568
	16. The analytics department is clear about its performance standards.	0.871
BDATEC [9,12]	1. Our firm possesses the best big data analytics systems compared to competitors.	0.837
	2. All remote, branch, and mobile offices are connected to the central office for analysis.	0.898
	3. Our firm utilizes open system network mechanisms to enhance analytical connectivity.	0.874
	4. In analytical discussions, our firm perceives no identifiable communication bottlenecks internally.	0.623
	5. Software applications can be easily transferred and processed across multiple analytical platforms.	0.927
	6. The user interface provides transparent access to all platforms and applications.	0.833
	7. Analytically driven information is comprehensively shared within our firm.	0.705
	8. Our firm provides numerous analytical interfaces or information entry points for external users.	0.702
	9. Reusable software modules are widely utilized in the development of new analytical models.	0.880
	10. End-users can create their own analytical applications using object-oriented tools.	0.892
	11. Our firm employs object-oriented techniques to reduce development time when creating new analytical applications.	0.845
	12. The applicability of applications meets various needs during analytical tasks.	0.504

Table 2. *Cont.*

Variable	Items	Loadings
BDATAC [9,12]	1. Our firm′s analysts possess high technical skills in coding.	0.791
	2. Our firm′s analysts are highly capable in managing the entire project lifecycle.	0.859
	3. Our firm′s analysts are very skilled in data and network management and maintenance.	0.704
	4. The decision-support systems established by our firm′s analysts are highly efficient.	0.800
	5. Our firm′s analysts have a profound understanding of technological trends.	0.535
	6. Our firm′s analysts demonstrate strong learning abilities for new technologies.	0.848
	7. Our firm′s analysts are well aware of the key factors for organizational success.	0.840
	8. Our firm′s analysts clearly understand that big data analytics is viewed as a tool.	0.848
	9. Our firm′s analysts have a deep understanding of organizational policies and plans.	0.791
	10. Our firm′s analysts can adeptly interpret business issues and develop appropriate technological solutions.	0.520
	11. Our firm′s analysts have a strong understanding of business functions.	0.827
	12. Our firm′s analysts are well-informed about the business environment.	0.863
	13. Our firm′s analysts excel in planning, organizing, and leading projects.	0.870
	14. Our firm′s analysts are adept at planning and conducting work in a collaborative environment.	0.572
	15. Our firm′s analysts possess strong teaching abilities.	0.891
	16. Our firm′s analysts maintain close contact with clients and establish good customer relationships.	0.862
Environmental Ethics [55,59]	1. Our firm has clear and specific environmental policies.	0.781
	2. Our firm′s budget planning includes considerations for environmental investments or procurement.	0.903
	3. Our firm integrates its environmental planning, vision, or mission into its marketing activities.	0.738
	4. Our firm incorporates its environmental planning, vision, or mission into its corporate culture.	0.902
GRI [3,5]	1. Our firm develops a new generation of eco-friendly innovations in its products and services.	0.918
	2. Our firm is implementing significant organizational changes to align with its focus on green innovations.	0.789
	3. Our firm is also interested in offering unprecedented experiences in green technology.	0.912
	4. Our firm emphasizes new radical environmental thought.	0.814
	5. Our firm establishes innovative green distribution channels.	0.962

Table 3. Reliability and validity analysis.

Variables	KMO	Alpha	CR	AVE
BDAMC	0.890	0.853	0.964	0.636
BDATEC	0.900	0.842	0.955	0.645
BDATAC	0.917	0.875	0.962	0.617
Environmental ethics	0.857	0.789	0.901	0.696
GRI	0.853	0.769	0.945	0.777

Table 4. Results of confirmatory factor analysis.

	Fit		χ^2/df	RMSEA	SRMR	CFI	TLI
1	Single-factor model	BDAMC + BDATEC + BDATAC + EE + GRI	1.446	0.039	0.043	0.903	0.899
2	Two-factor model	BDAMC + BDATEC + BDATAC + EE; GRI	1.423	0.038	0.043	0.908	0.905
3	Three-factor model	BDAMC + BDATEC + BDATAC; EE; GRI	1.415	0.037	0.042	0.91	0.906
4	Four-factor model	BDAMC + BDATEC; BDATAC; EE; GRI	1.411	0.037	0.042	0.911	0.907
5	Five-factor model	BDAMC; BDATEC; BDATAC; EE; GRI	1.410	0.037	0.042	0.912	0.907
	Criteria		<5	<0.08	<0.08	>0.9	>0.9

3.4. Common Method DeviationTest

We assessed common method bias using Harman's single-factor test and the unmeasured latent method construct (ULMC) test [73]. For Harman's single-factor test, the results

showed that 10 factors with eigenvalues greater than 1 were identified, which together explained 55.22% of the total variance. The variance explained by the first factor was 34.94% (less than 50%). Therefore, there is no serious common method bias issue in this study.

4. Results

4.1. Descriptive Statistics Results

Table 5 presents the correlation coefficient matrix among the variables and the variance inflation factor. Additionally, descriptive statistics including means and standard deviations were reported using SPSS 26.0. It can be observed that there are significant correlations ($p < 0.01$) among BDAMC, BDATEC, BDATAC, environmental ethics, and innovation performance. This provides preliminary support for the regression analysis. Furthermore, since the VIF values for all variables are well below the critical value of 10, this indicates that the regression model does not suffer from serious multicollinearity issues.

Table 5. Correlation analysis and variance inflation factor analysis.

	1	2	3	4	5	6	7	8	VIF
1	1								
2	0.605 ***	1							3.96
3	0.616 ***	0.825 ***	1						4.33
4	0.632 ***	0.824 ***	0.837 ***	1					4.34
5	0.493 ***	0.603 ***	0.619 ***	0.627 ***	1				1.76
6	0.098 *	0.120 **	0.035	0.110 *	0.044	1			1.41
7	0.076	0.082	0.026	0.09	0.009	0.303 ***	1		1.11
8	−0.155 ***	−0.124 **	−0.142 **	−0.144 **	−0.131 **	0.442 ***	0.131 **	1	1.31
Mean	3.348	3.318	3.258	3.316	3.369	2.333	3.732	2.789	4.058
S.D.	0.727	0.622	0.674	0.658	0.741	1.537	0.904	0.892	1.064

Note: 1.GRI; 2. BDAMC; 3. BDATEC; 4. BDATAC; 5. environmental ethics; 6. firm size; 7. R&D intensity; 8. firm age. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

4.2. Hypotheses Results

This study employs regression analysis to test the hypotheses. The regression results are presented in Table 6. Model 1, as presented in Table 6, includes BDAMC, BDATEC, BDATAC, GRI, and relevant control variables and is employed to test Hypotheses 1–3. As shown in the results, BDAMC is significantly positively correlated with GRI (b = 0.212, $p < 0.05$). Hypothesis H1 is supported. BDATEC is significantly positively correlated with firm innovation performance (b = 0.231, $p < 0.05$). Hypothesis H2 is supported. BDATAC is significantly positively correlated with GRI (b = 0.279, $p < 0.01$). Hypothesis H3 is supported.

As shown in Table 6, Model 2 indicates that the interaction term between BDAMC and environmental ethics is significantly positively correlated with GRI (b = 0.105, $p < 0.1$). Additionally, BDAMC itself is positively correlated with GRI. This finding suggests that corporate environmental ethics positively moderates this relationship. Furthermore, as illustrated in Figure 2, the slope of the line is steeper in high environmental ethics situations, indicating that in contexts with higher levels of environmental ethics, BDAMC has a stronger positive effect on GRI. Therefore, Hypothesis 4 is supported.

In Model 3, the interaction term between BDATEC and environmental ethics is significantly positively correlated with GRI (b = 0.153, $p < 0.01$). BDATEC is also positively correlated with innovation performance. This indicates that environmental ethics positively moderates the relationship. As illustrated in Figure 3, the slope of the line is steeper in high environmental ethics situations, indicating that BDATEC has a stronger positive effect on GRI in such environments. Therefore, Hypothesis 5 is supported.

Table 6. Regression results.

Variables		Model Base	Model 1	Model 2	Model 3	Model 4	Model 5
BDAMC	H1		0.212 **	0.192 *	0.192 *	0.197 *	0.192 *
			(1.997)	(1.816)	(1.827)	(1.861)	(1.827)
BDATEC	H2		0.231 **	0.215 **	0.229 **	0.210 **	0.237 **
			(2.305)	(2.139)	(2.292)	(2.095)	(2.353)
BDATAC	H3		0.279 ***	0.250 **	0.235 **	0.252 **	0.221 **
			(2.644)	(2.361)	(2.234)	(2.392)	(2.091)
BDAMC × Environmental ethics	H4			0.105 *			−0.155
				(1.665)			(−1.140)
BDATEC × Environmental ethics	H5				0.151 ***		0.296 **
					(2.724)		(2.204)
BDATAC × Environmental ethics	H6					0.120 **	−0.031
						(2.076)	(−0.220)
Environmental ethics				0.094	0.100 *	0.095	0.114 *
				(1.588)	(1.716)	(1.611)	(1.920)
R&D		0.009	0.018	0.026	0.025	0.026	0.024
		(0.184)	(0.415)	(0.609)	(0.596)	(0.619)	(0.569)
Firm age		−0.100 **	−0.064 *	−0.058	−0.051	−0.057	−0.048
		(−2.376)	(−1.789)	(−1.628)	(−1.441)	(−1.595)	(−1.346)
Firm size		0.074 **	0.040	0.042	0.040	0.040	0.036
		(2.471)	(1.551)	(1.632)	(1.560)	(1.565)	(1.400)
Firm nature		0.039	0.051 **	0.045 *	0.043 *	0.044 *	0.044 *
		(1.333)	(2.030)	(1.825)	(1.728)	(1.782)	(1.782)
Is high-tech firm		0.257 **	−0.011	0.009	0.025	0.008	0.021
		(2.429)	(−0.119)	(0.099)	(0.267)	(0.084)	(0.224)
Industry type		Control	Control	Control	Control	Control	Control
Constant		3.007 ***	0.879 ***	0.723 **	0.685 **	0.721 **	0.666 **
		(10.143)	(2.718)	(2.190)	(2.089)	(2.188)	(2.026)
Observations		291	291	291	291	291	291
Adj R-squared		0.204	0.427	0.435	0.444	0.438	0.444
F		7.745	16.44	14.96	15.50	15.13	13.87

Note: t-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

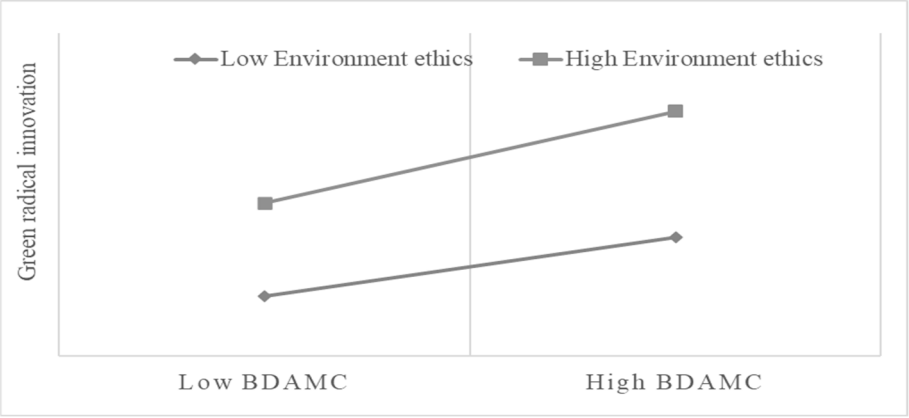


Figure 2. Moderating effect of environmental ethics on the relationship between BDAMC and GRI.

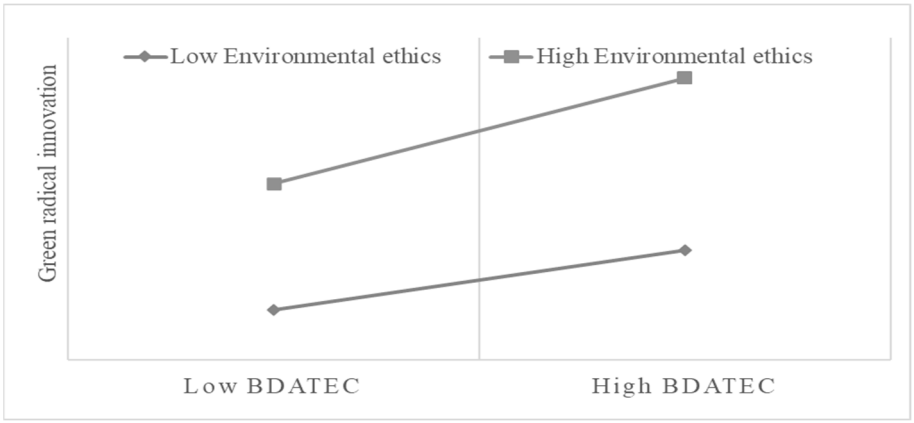


Figure 3. Moderating effect of environmental ethics on the relationship between BDATEC and GRI.

In Model 4, the interaction term between BDATAC and environmental ethics is significantly positively correlated with GRI (b = 0.122, $p < 0.05$). BDATAC is also positively correlated with GRI. This finding suggests that environmental ethics also positively moderates this relationship. Figure 4 illustrates this moderating effect, with a steeper slope in high environmental ethics contexts, indicating that BDATAC has a more pronounced positive impact on GRI when environmental ethics are elevated. Thus, Hypothesis 6 is supported.

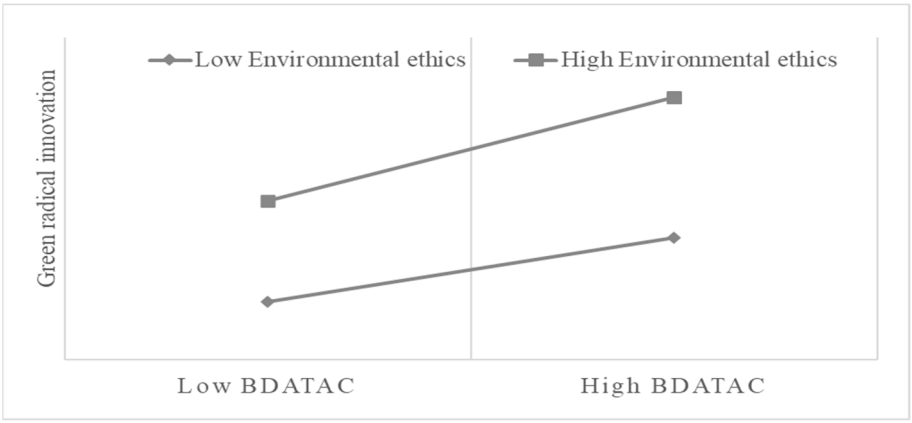


Figure 4. Moderating effect of environmental ethics on the relationship between BDATAC and GRI.

4.3. Post-Analysis

Additionally, this study tries to determine whether the effects of the different BDAC dimensions on GRI vary and whether the moderating role of environmental ethics differs across these dimensions. Based on the results of Model 1 in Table 6, it tested the relationships between BDAMC, BDATEC, BDATAC, and GRI; we further investigated the differences in the impact of different dimensions of BDAC on GRI. This study is based on Model 1. However, the empirical results do not confirm that the three different dimensions of BDAC have significant differences in their impact on GRI.

Furthermore, this study incorporates the interaction of BDAMC, BDATEC, BDATAC, and environmental ethics into Model 5. The results indicate that the interaction between BDATEC and environmental ethics is significant at the 5% level, while coefficients of the other two interaction terms are not significant. As shown in Table 7, this study further analyzed the significance differences in the coefficients, and the results reveal a significant difference between $\beta_{(\text{BDAMC} \times \text{environmental ethics})}$ and $\beta_{(\text{BDATEC} \times \text{environmental ethics})}$, with a coefficient of -0.450 ($p < 0.05$). This confirms that when considering the influence of environmental ethics, BDATEC has a more positive impact on innovation performance

compared to BDAMC, approximately 0.450 units. Further directional tests reveal that $\beta_{(\text{BDAMC}\times\text{environmental ethics})} < \beta_{(\text{BDATEC}\times\text{environmental ethics})}$, ($p = 0.024$). This may suggest that in today's rapidly evolving technological environment, advancements and innovations in big data technology far outpace management methods and practices. In a corporate culture that emphasizes environmental ethics, the application of technology capability tends to focus more on sustainability and social responsibility. This ethical orientation may lead to more innovative and forward-thinking technical solutions, thus playing a greater role in enhancing GRI. In contrast, BDAMC is more reflected in optimizing resource allocation, improving team collaboration, and facilitating knowledge sharing, which are all supportive functions.

Table 7. Significance test for differences about moderating coefficients.

	Coeff	*t*	*p*	[95% Conf. Interval]
$\beta_{\text{BDAMC}\times\text{Environmental ethics}} = \beta_{\text{BDATEC}\times\text{Environmental ethics}}$	−0.450	−1.98	0.048	[−0.897, −0.003]
$\beta_{\text{BDAMC}\times\text{Environmental ethics}} = \beta_{\text{BDATAC}\times\text{Environmental ethics}}$	−0.124	−0.55	0.590	[−577, 0.329]
$\beta_{\text{BDATEC}\times\text{Environmental ethics}} = \beta_{\text{BDATAC}\times\text{Environmental ethics}}$	0.326	1.35	0.178	[−150, 0.802]

There is no significant difference in the moderating effect of environmental ethics on the relationship between BDATAC and BDAMC with GRI. There is also no significant difference in the moderating effect of environmental ethics on the relationship between BDATAC and BDATEC with GRI. This may be because environmental ethics significantly shapes the overall culture and values of the organization, and this influence is both extensive and profound. Whether in the cultivation of talent or the optimization of management practices, environmental ethics may serve as a fundamental guiding principle, which may result in similar moderating effects on both. This leads to a lack of significant differences.

5. Discussion

Based on resource-based theory and ethical perspectives, this study analyzes the impact of a firm's BDAC (management, technology, and talent) on GRI and how environmental ethics moderate these relationships. As shown in Table 8, the main conclusion drawn is that BDAMC, BDATEC, and BDATAC have a significant impact on GRI and that environmental ethics positively moderates the positive relationships between BDAMC, BDATEC, BDATAC, and GRI. When considering the influence of environmental ethics, BDATEC has a more positive impact on innovation performance compared to BDAMC.

Table 8. Summary of hypothesis testing.

Hypothesis	Results
Direct effect	
H1: BDAMC→GRI	Supported
H2: BDATEC→GRI	Supported
H3: BDATAC→GRI	Supported
Moderating effect	
H4: Environmental ethics × BDAMC→GRI	Supported
H5: Environmental ethics × BDATEC→GRI	Supported
H6: Environmental ethics × BDATAC→GRI	Supported

Specifically, BDAMC promotes effective GRI by reasonably planning ahead, making efficient and orderly investments, coordinating various stakeholders, and achieving reason-

able control over BDA. BDATEC effectively enhances the connectivity of cross-functional data, compatibility across multiple platforms, and the modularization of data models, facilitating the rapid development and deployment of innovations, thus increasing innovation flexibility. The higher the BDATAC, the stronger the technical management, technical knowledge, and relational knowledge, leading to a richer innovation knowledge base that enhances the success of GRI. The higher the level of environmental ethics, the clearer the firm's environmental planning, the more comprehensive the relevant management, and the more sufficient the associated budget for supporting funds. These factors, both tangible and intangible, enhance the impact of BDAMC on GRI. When the level of corporate environmental ethics is high, firms tend to focus more on whether their decisions made through relevant technologies will impact the environment during related analyses. This, in turn, affects GRI flexibility. When environmental ethics are high, they can create a positive organizational atmosphere both internally and externally. This fully leverages the initiative and enthusiasm of BDATAC, leading to the development of products and services sourced from GRI that are competitive in the market.

5.1. Theorical Contribution

From the perspective of BDAC, this study contributes to the research on the mechanisms by which BDACs impact GRI. This study is based on three dimensions of BDA capabilities: BDAMC, BDATEC, and BDATAC. It finds that all three positively impact firm innovation performance, responding to calls for more granular research on BDAC [12,42,74], and it also further provides evidence of the positive impact of big data analysis capabilities on innovation [9,13]. However, this study did not find significant differences in the impact between different dimensions in the post analysis. Further, this study also identifies a positive moderating effect of corporate environmental ethics on the relationship between BDAC and GRI, thereby enriching the boundary condition research [15,16,18,75,76].

From the perspective of environmental ethics, this study contributes to the research on the mechanisms by which environmental ethics impact innovation performance [27,58]. It finds that environmental ethics enhance GRI by positively influencing the relationship between BDAC and GRI. It highlights the combined effect of environmental ethics and BDAC on GRI. With the rapid development of big data research, scholars have studied a range of ethical issues [77–79], including the need to conduct research using large databases while protecting data subject privacy and data subject ownership [80,81]. However, to date, the relationship between big data and environmental ethics has not received sufficient attention. Some researchers emphasize that this limitation hinders the understanding of how firms in the digital economy balance value creation with ecological concerns [30–32,78,82], affecting the functioning of data governance mechanisms, such as environmental policy formulation [28]. This study, combining the perspective of environmental ethics, identifies the positive moderating effect of environmental ethics on the relationship between BDAC and GRI, responding to Vial et al.'s [83] call for more research on the relevance of ethics in the impact of digital technologies. The results of this study provide new research avenues from an ethical perspective, enriching the research on data governance mechanisms.

Additionally, this study further contributes to the research on the heterogeneity of the role of environmental ethics [26,84]. The study finds that higher environmental ethics strengthen the impact of BDATEC on innovation performance more so than that of BDAMC. This highlights the importance of enhancing environmental ethics to better transform technical capabilities into innovation performance, offering new insights into how firms can effectively utilize their BDAC for sustainable development.

5.2. Management Implications

First, firms should prioritize the development of BDAMC. The results show that BDAMC has an impact on GRI. This involves strengthening the construction and management of operational databases to ensure data modularization, modeling, and chaining. By transforming raw data into valuable strategic resources, firms can establish a solid foundation for innovation performance. Additionally, robust data security measures, such as desensitization and encryption, must be implemented to safeguard sensitive information. Establishing data-sharing mechanisms that align with the business chain can unlock the latent value of data, thereby enhancing GRI.

Second, accelerating the BDATEC of firms is essential. The results show that BDATEC has an impact on GRI. Technological upgrades in BDA management systems, computational models, and business analysis tools can significantly enhance managerial decision-making. By leveraging BDA technologies, managers can gain deeper insights into business operations, identify deficiencies and bottlenecks in GRI, and clarify strategic directions for innovation. The comparative analysis of internal and external data further underscores the pivotal role of big data in operational management. It reinforces the firm's ability to adapt to evolving environmental challenges.

Third, the role of firms in incubating BDATAC should be emphasized. The results show that BDATAC has an impact on GRI. Governments and industry stakeholders must collaborate to create an integrated talent development model that involves academia, research institutions, and the private sector. Policy support for BDA talent cultivation, coupled with international talent exchange programs, can enhance the pool of skilled professionals. Furthermore, the establishment of robust talent incentive mechanisms and GRI systems can foster a culture of innovation.

Fourth, firms should promote environmental ethics as a core organizational value and establish exemplary practices that serve as societal benchmarks. Enhancing corporate environmental ethics is critical for maximizing the impact of BDAC on GRI. The development of technical standards for environmental ethics can create guiding and constraining mechanisms that align with GRI objectives. Additionally, the implementation of an assessment system for corporate environmental responsibility, coupled with regular public disclosures, can enhance transparency and accountability. Research indicates that when environmental ethics are considered, improvements in BDA technical capabilities may yield greater GRI than enhancements in management capabilities alone. Under resource-constrained conditions, firms should prioritize the synergistic development of BDATEC in conjunction with environmental ethics to achieve more significant GRI enhancements.

5.3. Limitations and Future Prospects

This study has several limitations. First, it analyzes the impact of BDAC on GRI from the perspectives of management, technology, and talent. Future research could explore other categories of BDAC and investigate the synergistic interactions. Second, this study examines the boundary conditions of environmental ethics. Future research could investigate the effects of other contexts or inherent traits (e.g., green corporate culture). Moreover, to enhance generalizability, future studies should validate our findings across diverse cultural and industrial contexts. Cross-cultural comparisons may further clarify how institutional and cultural factors moderate the effects of BDAC on innovation. Additionally, employing multiple tools and methods for the more precise measurement and handling of variables may be necessary. Given the reliance on cross-sectional data, the temporal dynamics of BDAC's influence on innovation remain unclear. Future research could adopt longitudinal designs to trace the evolving mechanisms through which BDAC shapes GRI trajectories and supports sustainability-driven strategic pivots. Finally, future studies should con-

sider integrated mixed-method approaches, combining large-scale longitudinal surveys to quantify the dynamics of ecological commitments with in-depth case studies to map multi-stakeholder communication networks, thus elucidating the mechanisms through which environmental ethics drive innovation.

6. Conclusions

This study employs resource-based theory and ethical frameworks to investigate how BDAC's different components, namely demission, managerial, technological, and talent, influence GRI, with environmental ethics serving as a moderator. This study reveals some significant findings: (1) All three BDAC components (BDAMC, BDATEC, and BDATAC) have an impact on GRI; (2) environmental ethics enhances the strength of these BDAC-GRI relationships; and (3) comparative analysis demonstrates that BDATEC exerts a stronger influence on GRI than BDAMC when environmental ethics are considered. This study has promoted innovation management research and environmental ethics research by advancing the understanding of the mechanisms through which BDAC influence GRI, thereby enriching the boundary condition research. Specifically, it highlights the synergistic role of BDAC dimensions (managerial, technological, and talent) in driving GRI while demonstrating how environmental ethics acts as a critical moderator that amplifies these relationships. Furthermore, this study contributes to the growing body of literature on the relevance of ethics in the context of digital technologies. By integrating ethical perspectives into the analysis of BDAC and GRI, it opens new research avenues for exploring data governance mechanisms and their alignment with sustainability goals. These insights not only deepen the theoretical understanding of innovation management but also provide a foundation for future studies on the interplay between digital capabilities, ethics, and environmental sustainability. From a practical perspective, the findings offer valuable guidance: Firms should strategically prioritize BDAC importance, particularly BDATEC, under consideration of environmental ethics to maximize GRI. This study underscores the potential of leveraging digital capabilities in the digital economy era to further advance sustainable development.

Author Contributions: W.W., validation, writing—original draft preparation and writing—review and editing; X.L. and G.R., Conceptualization, methodology, software, validation, writing—original draft preparation and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China, grant number 72472039 and 72072047; the fundamental research funds for the central universities, grant number HIT.HSS.ESD202310; the research project on graduates' education and teaching reform, grant number 23MS011; the Research Project on Higher Education of Heilongjiang Higher Education Association, grant number 23GJYBC011; and the Key Research and Development Program of Heilongjiang Province, grant number 2024ZXZLG02.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: The authors would like to extend our appreciation to all those who participated and contributed to this study. The authors would like to express their heartfelt gratitude to all individuals and institutions who have supported this research and appreciate the constructive feedback provided by the anonymous reviewers, which has significantly improved the quality of this manuscript.

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

Abbreviations

The following abbreviations are used in this manuscript:

BDA	Big data analytics
BDAC	Big data analytics capabilities
BDAMC	Big data analytics management capability
BDATEC	Big data analytics technology capability
BDATAC	Big data analytics talent capability
GRI	Green radical innovation

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