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An improving of green supply chain performance using green digital learning and artificial intelligence integration

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Abstract

The recognition of sustainability as a top supply chain management issue has led to the exploration of cutting-edge digital technologies such as Big Data Analytics and Artificial Intelligence (BDA-AI), along with the Artificial Intelligence of Things (AIoT), for environmental and operational enhancements. Guided by the research gap regarding the effectiveness of these technologies in green supply chain frameworks, this study aims to explore the direct and indirect impacts of using BDA-AI, AIoT integration, and Green Digital Learning on GSCP. The quantitative survey relied on data compiled from 184 industry professionals and was analyzed using Structural Equation Modeling – Partial Least Squares.4 (SEM-PLS-4). Industrial business functions indicate that BDA-AI positively affects GSCP in two pathways: a direct impact and an indirect pathway to Green Digital Learning, which has a strong moderating effect. AIoT integration was also a strong predictor of GSCP, implying that AIoT integration in the supply chain can improve resource allocation and process efficiencies. These results indicate that Green Digital Learning is vital for augmenting the sustainability effect of digitalization technologies by offering employees the ability to effectively apply data-based insights. The study makes a twofold contribution to academic literature and industry practice by proposing a reference model for energy sustainability while enabling digital transformation and providing managerial insights that, in turn, permit organizations aspiring to achieve a green supply chain through operational excellence.

Keywords: Artificial intelligence of things, Big data analytics, Green digital learning, Green supply chain performance, Supply chain sustainability.

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1. Introduction

As of the present time, only in the past few years has the integration of big data analytics (BDA) and artificial intelligence (AI) into green supply chain management facilitated transformative capabilities for operational and environmental performance. Each of its four components—blockchain, distributed ledgers, artificial intelligence (AI), and economics—has potential application in managing emissions, so long as they are used collectively to enhance data integrity and transparency [1-4]. Although opportunities are significant, empirical works reveal ongoing challenges in clarifying the mechanisms by which BDA-AI can improve environmental process integration and market competitiveness [5, 6]. However, for supply chain managers, embedding these tools within green supply chain frameworks is inherently difficult, as it requires aligning technological capabilities with environmental objectives. Managers are under pressure to meet sustainability challenges while maintaining operational efficiency, as the cost of environmental regulations increases and consumer behavior tends toward ecological concerns in high-stakes, competitive markets [7]. More specifically, one riddle to solve in this integration is the moderators, such as Green Digital Literacy, that can effectively catalyze employees' efficacy in the use of BDA-AI tools at work-related ecological moments. In this framework, digital learning is assumed to offer the relevant competencies required by employees in order to comprehend and apply data-driven insights that are compliant with sustainability objectives necessary for supporting organizations in reaching environmental process integration [1, 8]. This moderating function is particularly important in the sense of educating and stimulating employees to ensure that they can effectively leverage BDA-AI capabilities through digital learning, linking potential value with practical value. However, full-fledged green digital learning programs have failed to be systematically implemented by many organizations for multiple reasons, such as budget restrictions, scarcity of technological skills, and bureaucratic resistance [1]. This gap in green digital learning adoption points to a space for future inquiry, as organizations often wrongly invest a lot in technology but are not able to avail themselves of the environmental benefits that accompany it Feng, et al. [7]. Moreover, the Artificial Intelligence of Things (AIoT), which is the concept that integrates AI and the Internet of Things (IoT), presents a solution for going smart green in the supply chain [9-15]. AIoT, fusing the predictive nature of artificial intelligence and the data connectivity provided by the Internet of Things, allows for supply chain management processes that can be adjusted in real-time to reduce waste and improve resource utilization, thereby making efficiencies operational while maintaining sustainability [16]. This dynamic model opens the door to a new results-based economy that promises lower costs and automation with broad implications for green supply chain sustainability. Nonetheless, AIoT faces significant challenges in practical implementation, rooted in high costs, stringent data protection requirements, and compliance needs that act as barriers to the adoption of AIoT for many smaller organizations [17, 18]. As a result, although AIoT has great potential in sustainable manufacturing, its usage is not high enough to bridge the gap between technological capability and the practicality of green supply chains. This gap highlights a case for focused research on sustainable AIoT implementation strategies in light of regulations, costs, and security concerns [17]. Thus, the benefits for green supply chain performance through BDA-AI and AIoT are pronounced, as well as being impeded by inadequate digital pupillage frameworks, excessive implementation costs, and lack of regulatory pressure. Through an examination of the moderating role of green digital learning and possible paths for integrating AIoT, this research aspires to provide a holistic viewpoint on how to exploit technological advancements to enhance environmental process integration, market competitiveness, and overall sustainability in managing green supply chains.

2. Literature Review

2.1. Big Data Analytics and Artificial Intelligence

The use of big data analytics (BDA) and artificial intelligence (AI) in supply chain management has already reshaped green supply chain performance. BDA-AI in industrial system-driven organizations handles large-scale data for process optimization [1], real-time decision-making, long-term environmental impact forecasting, and market-environment goals alignment [2, 6]. The predictive capabilities of the proposed BDA-AI provide a backdrop for data-driven proactive strategies for resource allocation and sustainability management within supply chain operations. For example, machine learning and predictive modeling have enabled organizations to predict resource consumption, detect lapses in efficiency, and minimize waste throughout the supply chain, thereby creating avenues for practices aligned with environmental preservation. However, the literature exposes a gap in our knowledge regarding the direct impact that results from using these technologies to encourage integration within environmental processes; studies lack significant focus on deploying it to aid eco-friendly supply chains more broadly [5]. Moreover, while BDA-AI technologies have significant opportunities to enhance green supply chain management, substantial implementation challenges are faced in practice, driven by operational and social barriers. Indeed, the integration of BDA-AI into green supply chain frameworks will be complex since tying advanced technologies (i.e., BDA-AI) with environmentally sustainable actions and firms' other goals may not always be easy due to staff capabilities or organizational inertia layering among such topics [19]. This means, for example, that there is less extensive utilization of data in environmental terms through BDA-AI, often because many organizations do not have the skills or knowledge necessary to interpret and use data. Accordingly, the space in between remains highly lucrative for strategic frameworks that can connect technological capabilities to operational practicalities, especially in today's world, where customer demand is for sustainable practices in action [2]. Finally, for green digital learning, features as a moderating variable, it should not be ignored that the successful green supply chain will also depend on human input, and this new trend with BDA-AI in its potential use in GSC can confront two important challenges. In turn, green digital learning drives a culture change within the organization that focuses on sustainability and allows employees to understand data insights in terms of environmental objectives [1].

To empower employees, this training is key in establishing a continuous learning environment that perpetuates sustainable best practices while incorporating BDA-AI technologies into corporate sustainability objectives. Although green digital learning has the potential to be effective, existing work highlights its utilization issues or inadequate integration in most organizations due to economic restrictions [7]. In addition, other studies have explored the potential of green digital learning in contributing to the maximization of BDA-AI for environmental objectives without focusing on the technology itself. This gap may indicate the requirement for additional investigation into a more sustainable transformation of green supply chains: how digital learning can help organizations realize the full potential of BDA-AI. The convergence of artificial intelligence with the Internet of Things (IoT), also known as AIoT, summarizes many innovations in green supply chain management apart from BDA-AI. In the supply chain operational context, AIoT enables intelligent and interconnected real-time sensor-based systems that continuously monitor various process steps within the sensitive dimensions of agility (variability) [16]. They empower organizations to reduce waste, improve resource utilization, and cut down on their carbon footprint, aligning business efficiency goals with sustainability objectives. There are obstacles that prevent AIoT from being implemented on a large scale, such as high costs, data security necessities, and regulatory compliance. This may suppress the interest of generally smaller companies in applying this technology [17]. The notable contrast between the potential benefits of AIoT and real-world effects emphasizes that, in practice, success still requires sustainable strategies to overcome these adoption barriers.

2.2. Green Supply Chain Performance

Green supply chain performance (GSCP) has turned out to be an essential field of attention as organizations face more serious situations in which there is a necessity for their operations to align with environmental and sustainability desires. The GSCP goes beyond procurement and production practices to consider the greening of the supply chain across the lifecycle of goods, from logistics to waste. This comprehensive program will save energy and costs as well as significantly decrease environmental impacts, reinforcing its economic advantage, customer satisfaction, and compliance with regulations [1, 2]. Nevertheless, with only 2 percent of recycled plastic being utilized for food and drink packaging, it seems that progress on high GSCP is difficult to achieve at scale without a multifaceted strategy that incorporates technological innovation, sustainable sourcing, and process optimization. While it is critical, the system of GSCP is still complex, and many enterprises confront difficulties in synchronizing green practices across all supply chain functions, which evidences a gap between potential and practical implementation [7]. GSCP is powered by big data analytics and artificial intelligence (BDA-AI) to empower companies with the capabilities for data-driven decision-making and real-time responsiveness to complex, dynamic environmental changes for reducing waste, streamlining operations, and meeting sustainability objectives [5, 20]. It provides the ability to recognize where inefficiency exists, predict future resource requirements, and proactively manage environmental risks across the supply chain by offering transparency in green metrics using BDA-AI [1]. However, despite the widely acknowledged benefits of BDA-AI [21], organizations struggle to embed these technologies in green supply chains because of resource constraints and skill shortages among employees, hindering the achievement of intended innovation [2]. Building on this gap, the lack of strategic models connecting technology integration to green performance means that there are no tools yet to ensure BDA-AI optimizes its capacity as a driver for environmental process integration and market competitiveness.

The central importance of green digital learning in the successful moderation of GSCP has been identified as co-provisioning employees with the skills required to utilize BDA-AI responsibly within sustainable contexts. With the research of Benzidia, et al. [1] and Feng, et al. [7], it seems that GSCP is noticeably better when employee training for BDA-AI on sustainability is available to carry over information from environmental data, to decrease disputes with decision-making as a guarantee to eco-friendly modes in supply chain management. Nevertheless, very few green digital learning programs are available, especially for those organizations that do not have the resources or expertise to implement a full training framework. To the best of our knowledge, the literature on this subject emphasizes a similar void in research/upgrading of GSCP studies by accentuating directly the "skin effect" due to BDA-AI without tempering through green digital learning technologies for sustainable maximization. Filling in this void through digital learning could enable institutions to reach a level where there are employable people who can practice sustainable supply chain management and utilize BDA-AI tools [1].

AIoT combines artificial intelligence with the Internet of Things, joining these solutions to create smarter GSCP where the systems interact and are automatically adjusted based on environmental parameters. AIoT integrates predictive AI operations using real-time data from IoT devices to enable organizations to dynamically plan and control supply chain activities, thereby reducing waste generation while enhancing resource efficiency [16, 22]. For instance, reacting to real-time demand, AIoT can schedule the optimal inventory level, leading to output moderation and waste minimization that feeds directly into GSCP outcomes. Despite such benefits, challenges to the broad applicability of AIoT in green supply chains have included prohibitive implementation costs, data security needs, and regulatory requirements, which have particularly disadvantaged smaller firms [17]. Literature indicates that although AIoT offers great potential for GSCP, there is strong evidence of a number of adoption barriers and the importance of carrying out research on affordable strategies and regulatory frameworks that enable people to adopt AIoT [16].

Overall, the literature suggests that GSCP is critical in ensuring organizations develop environmental and competitive advantages from sustainable supply chain practices. While BDA-AI and AIoT appear to be key technologies that can contribute to enhancing GSCP, their integration effectively requires solutions to overcome issues associated with upskilling employees, resource provision (e.g., in terms of workforce availability), and technological hurdles. The purpose of green digital learning is to introduce the circular economy as a concept of green technology, teach how such new technologies can help with information overflow, and describe virtual work performance overcoming a clean context induced by the bureaucratic nature of bureaucracy, which defines and would help socially enable employees with the capability to embrace

BDA-AI intervention for sustainable development purposes. Nonetheless, the high cost and complex regulations associated with AIoT would require a strategic framework enabling affordable and regulatory-compliant AIoT adoption in green supply chains. Accurately addressing these gaps is essential to progress GSCP and allow organizations to fully reap the benefits of environmentally and operationally sound sustainable supply chain management.

2.3. Big Data Analytics and Artificial Intelligence Adoption

Big data analytics with artificial intelligence has gained significant importance in supply chain management (SCM), especially for green supply chain (GSC) initiatives to improve environmental and operational performance. BDA-AI technologies bring the capability to enterprises to process and execute real-time decision-making predictive analytics and advanced insights for their supply chain operations, which are vital when aligned with sustainability objectives [1, 2]. Organizations that reduce waste and can better predict resource demand will already be meeting both environmental sustainability and competitive advantage priorities; BDA-AI helps these companies achieve the same. Although BDA-AI offers multiple potentials, many organizations face both technical and managerial issues in properly implementing them and fail to obtain superior performance in the green supply chain [5]. The literature points to barriers in BDA-AI adoption, including high implementation costs, gaps in the required skills, and resource limitations that restrict organizations from complete integration of these technologies into operations. BDA-AI systems are more likely to be used by organizations that have external sources of expertise because the data and algorithms they incorporate—at large volumes, high velocities, or variabilities — [22] are potentially too costly in terms of both skills and staff for small and medium-sized enterprises to absorb, particularly if they wish to commence practice with analytics and AI [7]. Besides, the operationalization of BDA-AI with green supply chain programs not only calls for technical investments but also an organizational metamorphosis towards data-driven decisions and sustainable behaviors. This necessity for cultural change, however, is met with resistance from employees who may not want to adopt new technologies in organizations if traditional processes are ingrained in an individual's behavior [1]. These hurdles to adoption highlight the need for strategic frameworks to assist organizations in overcoming challenges associated with BDA-AI and help them leverage these tools to enhance environmental sustainability and operational efficiency.

To address the adoption barriers, green digital learning can be practiced as a mechanism that might foster BDA-AI adoption towards better GSCP by training employees to use insights from data for sustainable goals [1]. Green digital learning offers courses that aim to support employees in developing a better understanding of how BDA-AI can contribute to environmental targets by enabling staff to read complex data and apply findings for the purpose of waste prevention, utilization, and efficiency enhancement, as well as overall environmental sustainability [7]. Nevertheless, green digital learning is still a largely untapped field primarily due to resource constraints, the absence of formal programs, and inadequate attention to its value in supporting wider BDA-AI adoption. This lack of training and development identifies a fundamental contribution for future research, following organizations so they can maximize the environmental benefits provided by BDA-AI, to cope with Benzidia, et al. [1] indicating that digital learning frameworks that effectively support their workers in deploying these technologies are necessary. Furthermore, the intersection of AI and the Internet of Things (IoT), dubbed the Artificial Intelligence of Things (AIoT), indicates a profound development in BDA-AI implementation for green supply chains. The incorporation of AIoT between the powerful analysis capabilities provided by AI and the real-time data tracking enabled by IoT has made it possible to set up intelligent and interconnected systems that can monitor supply chain processes in real time [16] and react dynamically to comply with environmental goals [23]. By allowing for adaptive responses to environmental circumstances while curbing pollution levels, these organizations can deploy this integration with increased automation, cost efficiency, and sustainability. Yet, while AIoT has considerable potential in the context of sustainable supply chain practices, the latter has experienced hurdles to its adoption due to high costs [17], data management complexities, and strict regulatory regimes. These challenges are especially hard-hitting for small firms that may have low revenue generation to spend on full-fledged AIoT infrastructures, so affordable, modular solutions must be provided. AIoT has the potential to significantly improve BDA and AI adoption in greening supply chains, but research on novel cost-effective strategy frameworks and regulations to support integrated AIoT within SC needs further investigation for a sustainable ecosystem.

To conclude, these studies highlight the revolutionary aspects of BDA-AI and AIoT for sustainable supply chain performance, but at the same time, there are still vast adoption and optimization gaps to be filled. The BDA-AI adoption is a very expensive, skill-short minefield that creates cultural resistance towards the effectiveness of the green supply chain. This is where green digital learning enters as a crucial mediator to reduce these deficits and nurture in companies the competence to carry forward using BDA-AI effectively for environmental ends. Furthermore, AIoT showcases itself as a promising next frontier for advancing BDA-AI adoption but requires addressing real-world issues and regulatory concerns in order to fully materialize. Closing these BDA-AI and AIoT adoption gaps is critical for green supply chain performance improvement, and organizations must work to overcome the means-ends misalignment problem to facilitate environmental goals as well as operational ones

2.4. The integration of Artificial Intelligence of Things (AIoT)

The Natural Intelligence of Things (AIoT), the union of Artificial Intelligence and the Internet of Things, has shown to be a novel piece in Green Supply Chain Management, providing strong perspectives on how far it can enhance both environmental and operational performance. Moreover, systems interconnected through AIoT integrate real-time data generation with predictive analytics that allow supply chains to be dynamically monitored, rapid decisions to be made, and processes to be adjusted automatically [16, 24]. AIoT combines the IoT's continuous data flow with AI's analytical capabilities, improving supply chain automation, cost efficiencies, and environmental sustainability by reducing waste and optimizing resource utility [17]. AIoT-based infrastructure can manage energy consumption, anticipate demand fluctuations, and amend production programs to avoid excessive resource waste and maintain sustainable operations. Although the benefits of integrating AIoT represent remarkable opportunities, it also carries certain challenges that restrict its uptake and are particularly challenging for SMEs, which may not be able to sustain the costs and complexity of AIoT infrastructure [5].

One of the primary advantages of AIoT in green supply chains is that it opens up opportunities for autonomously brainstorming operational efficiencies and environmental goals by fusing to create smart, responsive systems. Real-time data processing of AIoT allows companies to face disruptions in the supply chain, adapt production rates according to market conditions, and manage inventory dynamically, contributing favorably to the environmental footprint generated by supply chain activities [1]. AIoT enables an agile and eco-friendly supply chain thanks to applications like smart warehousing, automated logistics, and energy-efficient manufacturing. Nevertheless, research has shown that while AIoT systems have huge potential, challenges in data management [16], cybersecurity, and compliance with environmental requirements are significant barriers to their large-scale adoption. In addition, with respect to data privacy and security, especially, the real-time capabilities of AIoT may oppose the availability of a secured kind of linearly managed supply chain settings where companies and their flows of data together specify multiple stakeholders located at regional levels [17].

In addition to these limitations, the expense of rolling out AIoT is a major bottleneck to adoption, which presents difficulties for other enterprises, mainly due to the high costs for SMEs. AIoT is generally achieved by integrating IoT-enabled devices with AI models utilizing cloud storage and adding cybersecurity, which requires a higher amount of infrastructure; hence, smaller organizations with lower budgets find this investment non-viable [2]. Moreover, the necessity of high-order technical capabilities to maintain and analyze AIoT data, as well as interpret it, also delays adoption since many are working with resources without the skilled manpower to exploit it in order to unlock its capacity [7]. This skill gap delineates an important future research and development area as organizations look for AIoT systems that can be easily and affordably adopted, driving performance by turning green their supply chains in a financially sound and human-resource-light manner. This gap is of particular concern in the context of sustainability in sectors where stakeholders impose increasing pressure on actors to incorporate sustainable practices, but significant capital expenses and the lack of resource availability still pose severe barriers [16, 25].

Besides, the control factors and moral effects are also supposed to have large impacts on AIoT implementation in inexperienced supply chains. As AIoT collects and processes a massive amount of data, organizations have to be more careful while crossing legal lines, as there are strict laws about data privacy (both in acquiring and processing) and environmental standards [26, 27] industry-specific laws [28]. However, the absence of common frameworks and policies for AIoT application in supply chains creates dilemmas for firms striving to innovate while following regulations. Environmental issues, such as energy consumption and emission standards, might require implementing extensive reporting or compliance measures for AIoT systems, which could impose additional operational costs and hurdles [5]. Moreover, ethical issues regarding the usage of AIoT further complicate this area, as organizations have to comply with regulations but also consider their societal impact on data collection [29], which is essential for public trust in the green supply chain. Ultimately, customers could use AIoT, e.g., blockchains, as an assurance tool in checking the impacts of business operations [1]. AIoT has the ability to redefine green supply chains, and apart from improving environmental performance, it will also lead to operational efficiency in terms of dynamic and data-driven responses. This real-time aspect of the technology can provide opportunities for better supply chain responsiveness, resource utilization, and waste reduction while meeting both sustainability and competitiveness goals. However, AIoT adoption has not fully extended to green supply chains because of high costs, concerns about data security, regulatory requirements, and the holistic expertise required in resource-constrained SMEs. Standardized regulatory frameworks to support future research in scalable and low-cost solutions for AIoT are essential to realize eventual impact and savings via AIoT-enabled supply chain sustainability. Solving these gaps would unlock the capabilities of AIoT for organizations and ensure that it is used in a manner that aligns with sustainability goals, making the technology an effective lever towards greener, more resilient supply chains.

2.5. Green Supply Chain Management Practices

Due to globalization and increasing environmental concern, Green Supply Chain Management (GSCM) practices have become popular worldwide as they compress both economic performance and environmental sustainability. This body of research includes a variety of supply chain practices to reduce their environmental footprint, such as green procurement (GP), eco-design, sustainable production, and waste management [7]. Practicing these actions helps enterprises align with regulatory standards, optimize resource usage, and support increased consumer awareness of eco-friendly businesses. However, creating GSCM practices still imposes certain challenges: high costs, complex process operations, and required technological insertion [1]. Accordingly, although integrated GSCM has the potential to promote sustainable growth [2, 16, 20, 22], there is still a lack of research that can provide new evidence regarding which specific functions and processes in businesses lead to more positive outcomes for integrating environmental dimensions with economic goals [2]. Being one of the key practices in GSCM, green procurement is related to obtaining materials and parts from suppliers that comply with environmental standards. Green procurement decreases the ecological effect of raw materials and sustains a sustainable supply chain from the start [1]. Green procurement has been shown to improve the sustainability profile and competitive position of a company, particularly in industries under high regulatory pressure or with extensive consumer expectations regarding sustainability [7]. However, many green procurement practices are labor- and cost-intensive, and they can be difficult to enforce without a transparent vetting system that may prevent some organizations, especially smaller firms, from fully embracing them. Thus, a need exists for research that investigates the costly dimension of green procurement strategies and different modes to construct supplier collaboration and urge sectors to adapt GSCM by rising new practicable frameworks [5].

GSCM also includes eco-design and production, which refers to designing products that have the least amount of impact on the environment from cradle to grave. Companies can reduce waste and increase operational efficiency by using materials that are climate-neutral, resource-saving, or recyclable [16]. One example, eco-design, has shown effectiveness in resource consumption and waste generation reduction, but the adoption of this strategy means investments in technologies and innovations (GRAEDENER, 2013), resulting in changes to product development processes. In addition, the key strength of implementing eco-design within supply chains requires coordination among various partners, including raw material suppliers to end-product distributors, which is exceptionally intricate [17]. Thus, while eco-design offers potential benefits as a means of enabling sustainable manufacturing [7], many organizations might struggle to measure and improve the environmental performance of their designs due to a lack of standardized approaches and tools. Therefore, the construction of eco-design frameworks and standards should contribute to a more standardizable material in GSCM practices that is desirable for consistent and quantifiable environmental benefits.

Waste management is a major area under GSCM with the aim of reducing waste throughout the supply chain and managing the disposal or recycling of materials [5]. For example, waste management practices in GSCM are evolving from point estimations to modeling and simulation using big data analytics (BDA) coupled with artificial intelligence (AI), which unveil trends of waste generation and facilitate data-driven decisions for more waste reduction. These urban waste management technologies enable organizations to streamline their waste removal and recycling strategies, which ultimately ensure both environmental impact and operational efficiency improvements [1]. BDA-AI in Waste Management: BDA-AI integration with waste management needs high investment costs and technical expert help, which are not easily approachable by most organizations, especially SMEs. The literature suggests a dire need and scope for solution methods of GSCM practices such as BDA-AI that can be scalable, cost-effective, and accessible to a variety of organizations [16]. The latter are also driven by green digital learning and artificial intelligence of things (AIoT) technologies, which promote the adoption of GSCM practices. Thus, green digital learning contributes to sharpening the skills and knowledge of employees to implement the required sustainable practices in the supply chain and hence be in a position to use BDA-AI for environmental goals [1]. AIoT is based on combining AI and IoT, which enables supply chains to make changes dynamically in their way of performing by aligning with sustainability objectives as they can track emissions and the amount of resources used in real-time [17]. In combination, these are game changers in GSCM that enable companies to develop human resources capable of deploying sustainability technologies and building "smarts" into their supply chain for environmental improvement. Nevertheless, the adoption of these tools still faces high costs, complex regulatory requirements, and a generic lack of technical capability [5].

To sum up, GSCM practices have a pervasive role in realizing sustainability objectives within supply chains through green procurement, eco-design, waste management, and utilizing digital trends like BDA, AI, and AIoT. Although these practices are lucrative, their adoption is limited by financial, technological, and operational constraints. More research is required to enhance frameworks and tools to tackle these issues for a wider applicability of GSCM practices across different sectors. Organizations can thus use this insight to improve the understanding of conducive conditions and support systems for the effective implementation of GSCM, which in turn will allow organizations to mainstream sustainability within their supply chains with tangible environmental as well as competitive benefits amidst a market driven by concerns toward sustainability.

2.6. Moderating effect of Green Digital Learning

Recently, green digital learning has been identified as an essential enabler for enhancing the implementation of green supply chain practices through training and sharing knowledge linked to sustainability in an era of advanced technologies such as big data analytics (BDA) and artificial intelligence (AI). Green digital learning endows employees with the required skills and knowledge to properly utilize BDA and AI for sustainability goals by enhancing environmental process integration and operational efficiency Benzidia, et al. [1]. It enables organizations to educate and train their workforce on sustainability and how they can interpret data insights to take action in a way that matters environmentally while also aligning with their operational goals. As powerful as it might be, an empirical study, to the best of our knowledge, has yet to be explored on green digital learning in the moderating relationship between BDA, AI, and green supply chain performance [7]. This means that the moderating role of green digital learning is quite crucial in facilitating the organizational capacity to bridge BDA and AI capabilities with sustainable-related outcomes. While companies can use BDA and AI for extensive data analysis leading to various conclusions, without adequate training, employees may not know how this data translates into practices that could be used within the green supply chain [5]. Green digital learning helps by providing the required skills to analyze complex data and evaluate environmental impacts as well as operational strategy options to enhance their sustainability profile. Employees instructed in green digital learning can, for example, use insights from AI to reduce waste, track and manage resource consumption, or enhance eco-efficiency. These findings are consistent with earlier results by Benzidia, et al. [1], who also found a mediating effect of digital learning, justifying the claim that educating employees within an organization can significantly help the organization better translate sustainability data into appropriate actions. While green digital learning offers numerous benefits, due to multiple factors, organizations may not be able to develop holistic sustainability training programs. The adoption of green digital learning frameworks can help public organizations overcome these barriers, but without this commitment and varied strategies, there is no way that technology use will be successful in the absence of an environmental agenda. The costs and complexities involved in digital learning implementation within operational practice, especially the problems faced by smaller firms, would pose an imposing barrier for them to fully benefit from BDA and AI when applying it for green supply chain management. Therefore, the literature highlights the importance of easily adoptable and low-cost green digital learning solutions that can be integrated into different organizational contexts, operating as a key enabler for resource-scarce organizations to improve their sustainability performance [7].

The phenomenon of green digital learning moderates more than just individual capabilities; it is also a catalyst for creating an organizational culture of sustainability. A sustainability-literate workforce is likely to prioritize environmental objectives, foster eco-innovation, and aid in nurturing a culture of continual advancement [17]. In this way, green digital learning not only equips employees with the skills to be effective change agents at a personal level but also begins to address wider supply chain activities and organizational resilience through increased advocacy of sustainability practices. A much-quoted Gartner statistic indicates that most organizations realize less than 3% of the potential value from their Business Data Analytics and Artificial Intelligence (BDA-AI) technologies; a combination of funding, talent, organizational, or trust issues prevents them from scaling up or out. Nevertheless, as emphasized by Zamani, et al. [5], even though the model has accounted for digital learning when linking green digital learning to sustainability outcomes, this body of research continues to demand a deeper understanding of the processes through which GDL affects sustainability outputs, as most studies seem to be absent from exploring the indirect effects of BDA-AI and its interaction with initialized or de-initialized learning on these processes [30].

In addition, with the University of West Florida proposing green digital learning for expansion pathways to fuel the use of artificial intelligence combined with AIoT and other emerging technologies in developing Big Data solutions in Green Supply Chain Management. AIoT is the incorporation of artificial intelligence technologies with IoT networks to optimize services and resource allocation in real time [16]. Given the complexity of such systems, digital literacy at a high level and environmental consciousness (two aspects that green digital learning can address) would need to be developed in employees so they could interpret data and respond with a sustainable approach [31]. Organizations risk not realizing the full potential of AIoT for green supply chain improvements if employees are not trained to access and leverage its results in real time [17]. Such a gap highlights the importance of green digital learning as a means to improve not only the effectiveness of BDA-AI but also that of AIoT to meet environmental targets.

In conclusion, green digital learning acts as a key moderating enhancer in improving green supply chain performance with BDA-AI by empowering employees equipped with the necessary competencies to operationalize data insights to facilitate sustainable outcomes. As such, it helps bridge the divide between what could be achieved in terms of potential technological solutions and more practical sustainability applications, helping to create a set of employees who accept environmental objectives both as desirable and operational.

Further research trajectory: Despite the frustration experienced by very small firms in implementing digital learning frameworks, its moderating effect illuminates an important avenue for future research and development. Download the report to learn about additional use cases and approaches that organizations can leverage to overcome these challenges and take full advantage of green digital learning, BDA-AI, and AIoT to build supply chains that are in accordance with changing environmental regulations as well as competitive expectations from competitors.

3. Hypothesis Development

In the recent past, big data analytics (BDA) associated with artificial intelligence has significantly transformed the paradigm of supply chain management (SCM), especially in terms of green supply chain performance. Companies that use BDA and AI reach data-driven insights to support green optimization of their products as legal obligations, Benzidia, et al. [1]. These enabling technologies that support predictive analytics and real-time decision-making are essential for facilitating the integration of supply chain operations with environmental goals, in addition to providing real-time responsiveness to market dynamics [2]. For instance, businesses can leverage BDA-AI to monitor their resource usage, cut down on emissions and waste, among other factors, in a bid to incorporate sustainability into their own supply chain activities. Although the literature has shown the benefits of BDA-AI, no study has delved into how much the adoption of this technology would result in a direct enhancement of green supply chain performance as a whole, not particularly with respect to environmental integration and market competitiveness [5]. By doing so, this study attempts to fill this gap, suggesting that BDA-AI has a potent effect on green supply chain performance via effective environmental process integration and competitive advantage. Thus, we hypothesize:

$H_{1:}$ Big data analytics and artificial intelligence (BDA-AI) influence green supply chain performance in terms of environmental process integration and market competitiveness.

Another significant solution for enabling green supply chain management systems (SCMS) is the Artificial Intelligence of Things (AIoT), which is included in both AI and IoT, or more commonly known as “the integration of artificial intelligence with the Internet of Things.” It results from combining AI's predictive power and IoT's real-time data gathering, which allows for the creation of interconnected, dynamic supply chains that adapt to environmental modifications [16, 32-36]. AIoT systems support these objectives by allowing organizations to optimize resource utilization, reduce waste, and align supply chain planning with their sustainable goals through automation, such as in automated warehousing, smart logistics, and monitoring energy-efficient resources. A number of studies illustrate that AIoT can dramatically improve supply chain agility by enabling design and production processes to be modified overnight based on real-time data, thereby reducing environmental impact and increasing resource efficiency [17]. While these AIoT benefits are well documented, scaling the integration of AIoT with green supply chain management practices still requires further investigation across various industry contexts [2]. From these, we derive a hypothesis for the purpose of this study:

$H_{2:}$ The integration of Artificial Intelligence of Things (AIoT) influences green supply chain management practices.

For green digital learning, an organizational focus on sustainability-oriented digital training plays a vital role in maximizing the impact of advanced technologies like BDA and AI within green supply chains. By equipping employees with the skills and knowledge to apply data insights in environmentally responsible ways, green digital learning fosters a workforce capable of using BDA-AI tools to improve sustainability outcomes [1]. Green digital learning also enhances employees' ability to interpret complex data insights, facilitating more effective integration of BDA-AI insights into supply chain practices, such as waste reduction, energy management, and resource optimization [5, 37, 38]. Additionally, the literature suggests that while BDA-AI offers powerful insights, its practical application in green supply chains is often limited by employees' technical skills and understanding of sustainability principles [7]. By moderating the relationship between BDA-AI adoption and green supply chain performance, green digital learning can bridge this gap, enabling organizations to fully leverage the environmental and operational benefits of BDA-AI. Therefore, we hypothesize:

$H_{3:}$ Green digital learning moderates the relationship between big data analytics and artificial intelligence adoption and green supply chain performance.

Drawing from the above, this paper presents a set of hypotheses that can be further tested to shed light on how BDA-AI and AIoT enhance green supply chain performance in environmentally sustainable firms (with or without an emphasis on emissions reductions through supplier control), as well as the effect of green digital learning in propagating sustainable technology adoption. This paper will seek to fill such gaps in the literature by exploring these relationships, offering this study as a pursuit towards understanding the duality of digital innovation on both environmental and competitive supply chain objectives for organizations.

4. Research Model

The Theoretical Model in Figure 1 shows how BDA-AI influences Green Supply Chain Performance through the mediating factors of integration of AIoT and Green Digital Learning. Prior research underscores the significant positive contribution of BDA-AI in improving green supply chain performance, mainly by leveraging environmental process integration and competitiveness via a data-centric firm hold [1, 2]. Yet managing this integration can be tricky as support needs to be complementary, job purposes aligned, and here is where Green Digital Learning plays an essential role [7]. Furthermore, AIoT integration—a hybrid model where AI combines with IoT technology—extends it further towards greener supply chain practices by implementing real-time data collection and analysis, thus optimizing the whole supply chain while efficiently reducing waste and increasing resources [16, 17]. Nevertheless, the research model in Figure 1 offers a structure to examine the combined effect of BDA-AI and AIoT integration on green digital learning through green supply chain performance. The use of both direct and moderating effects in this model adds to the literature.

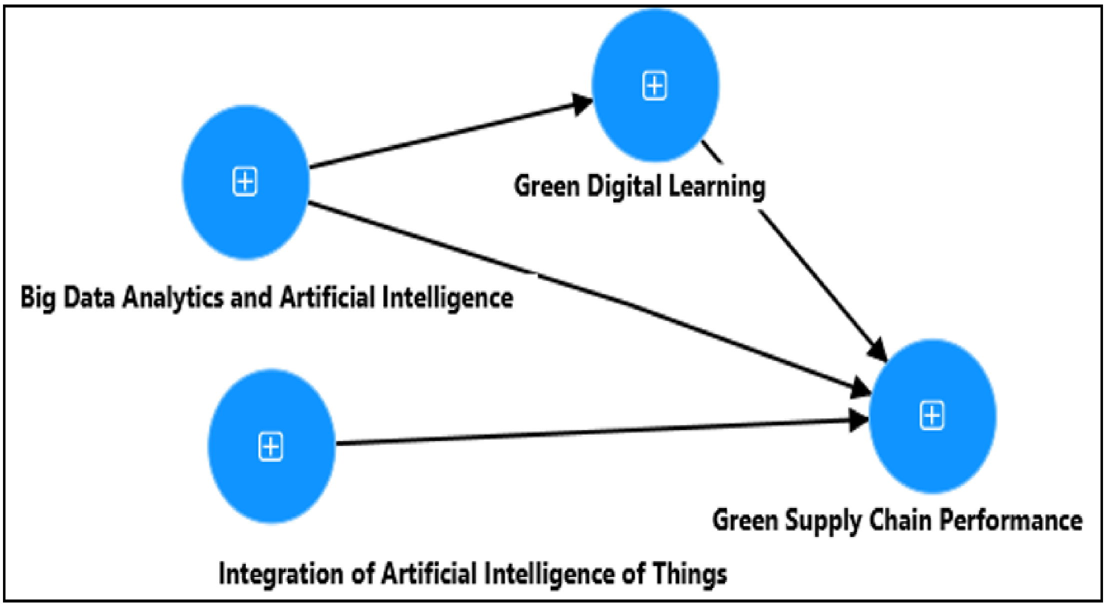

Figure 1.
Theoretical model.

The first step in the model measures the effect of BDA and AI on GSCP. Additionally, BDA and AI have transformative potential in terms of improving decision-making and operational inefficiencies, which allow organizations to comply with environmental standards and competitive needs [1]. Real-time insights, predictive capabilities, and advanced analytics through BDA-AI help to streamline environmental process integration across supply chains to extract greater efficiencies in resource usage, netting of emissions produced from operations, and embedding sustainability-related practices [5]. In addition, based on the prediction and data analysis ability of AI, it can provide enterprises with faster and more agile reactions, as companies will make their judgments guided by the invisible realities of market demands and sustainability expectations [2]. Similarly, the moderating effect of AIoT integration on green supply chain management practices is also studied in category two. Recently, AIoT, which integrates AI decision-making with IoT, enables real-time data tracking, automatic operation, and predictive maintenance as a brand-new dimension for developing an environmentally friendly supply chain action sustainably [16]. AI-based intelligent Internet of Things (AIoT) is a rapidly rising field that can empower smarter, self-regulating supply chains to utilize available data on environmental and operational parameters in real-time for adjusting processes, leading to reduced resource consumption and lesser waste generation [17, 31]. This technology helps manage and significantly improve tracking ability, which is crucial in various instances such as energy management, emissions, and sustainable logistics detection. However, as promising as AIoT can be, there are also certain challenges associated with its implementation, such as cost and regulatory compliance drawbacks, which might limit its scalability [2]. The last part of the research model regarding the impact of green digital learning in BDA-AI on green supply chain performance is moderated. Green digital learning provides employees with the knowledge and basic skills to deploy advanced analytics and AI for sustainability purposes, countering the negative consequences of a lack of technological capabilities in adopting technology effectively [1]. Green digital learning nurtures a culture of sustainability learning, which offers organizations an opportunity to maximize the ecological and operational dividends achievable due to BDA-AI by creating employees proficient in interpreting and translating data insights to eco-preferable ends [7]. This form of green digitization also enables perpetual learning; it helps create a workforce that is very efficient in utilizing digital tools for real-time decision-making related to green supply chains, considering the complexity of digital technology in being sustainable.

5. Methodology

In the current research, a survey-based methodology has been adapted to collect data and examine relationships among variables of the proposed model in a quantitative manner. This study adopted this method to quantify and explain the effect of Big Data Analytics and Artificial Intelligence (BDA-AI), along with the interrelation of the Artificial Intelligence of Things (AIoT), on green supply chain performance, moderated by Green Digital Learning [3, 9]. A structured survey approach is a valuable strategy for professionals with specific experience to gain insight into how these technological innovations are influencing sustainable supply chain practices. To collect data, the survey developed a structured questionnaire that was distributed to practitioners in supply chain management. Subjective norms and Perceived Behavioral Control were measured through the questionnaire, rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), allowing respondents to express their agreement with statements related to each variable. Validity and reliability of the instrument were assessed.

The face validity of the questionnaire was assessed through feedback from seven experts. Alterations were made according to their suggestions to ensure that the items accurately and clearly measured the denoted concepts [10, 39]. The selection of 184 professionals with extensive experience in the field was important, as it allowed for the analysis of more complex variables, such as BDA-AI and its integration into AIoT within green supply chain management practices [40]. A total of 169 responses remained after screening out incomplete replies, which included all outliers. This is a good sample size for running the SEM model in PLS, a suitable statistical technique for models with reflective and formative constructs that allows for the evaluation of latent variable relationships [41]. Data analysis was conducted using Smart PLS 4.1.0.4, a SEM tool that assesses direct relationships and the moderating role of Green Digital Learning in the relationship between BDA-AI and green supply chain performance [25]. SEM-PLS is particularly beneficial for dealing with complex models and detecting mediating and moderating effects, which is desirable for the nature of this study [42, 43]. This study examines the hypothesized relationships to establish a link between sustainable practices and SCM in an empirical sense, adding value to the conceptual framework on supply chain management practices with sustainability.

6. Results

6.1. Path Coefficients

This paper tested the path coefficient regarding the effect of the independent variable on the dependent variable. This indicates the strength and direction of the relationship between the two variables. It also utilizes R-Square, typically denoted as the coefficient of determination, to describe how much variance in the dependent variable is explained by the independent variable. In this model, the R^2 values for endogenous latent variables are all 0.67 or larger, indicating a significant positive relationship between exogenous and endogenous variables. A higher R^2 value means that the independent variable has a greater impact on the dependent variable. This was described in more detail in the research framework of achievement motivation and explained how different path effects for various factors to outcomes appeared (see Figure 2). The first work proposed a path model showing the relationships among three main constructs: Big Data Analytics and Artificial Intelligence, Integration of Artificial Intelligence of Things, and Green Digital Learning, along with their impact on Green Supply Chain Performance. In addition, every construct includes a number of measured items or indicators with unique labels (e.g., BDA-IA1 for Big Data Analytics and Artificial Intelligence; GDL1 for Green Digital Learning). Factor loadings (the numbers near each indicator) provide insights into which indicators capture them most effectively. The figures on the connecting paths among constructs are path coefficients indicating the extent of relationships between constructs in this model.

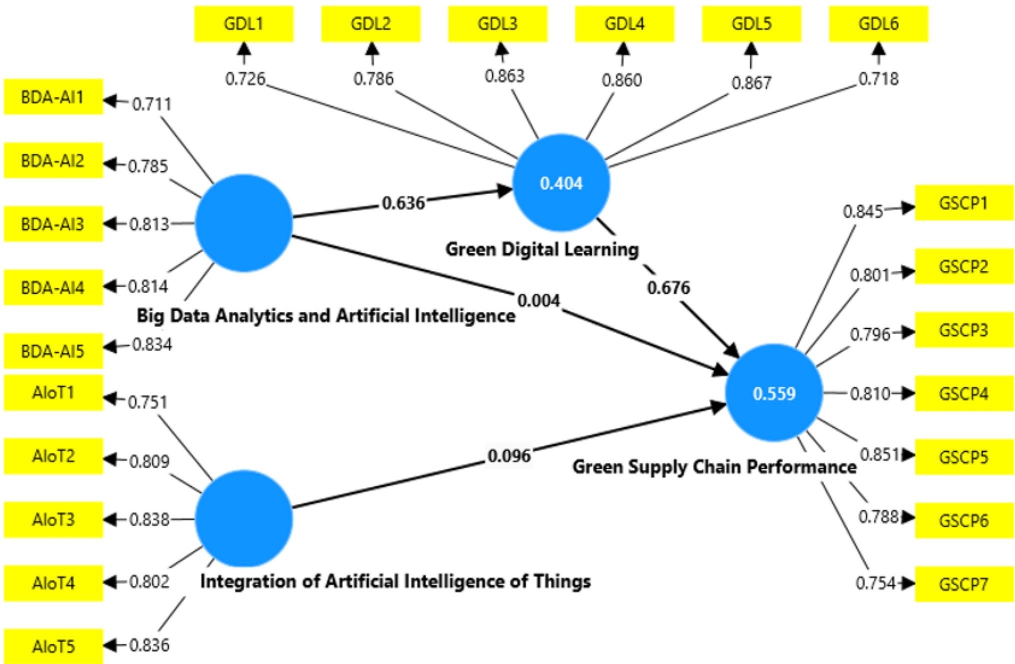

Figure 2.
Finalized measurement model (Validity testing).

The path model shows the interactions on which there is a moderation of racial/ethnic minority status. The variables underlying Big Data Analytics and Artificial Intelligence (BDA-AI) express high loadings, ranging from 0.711 to 0.834. The convergence here indicates that all dimensions of BDA-AI are highly reliable and important elements of the overarching construct. Integration of Artificial Intelligence of Things (AIoT) also has high factor loadings across the range of indicators (0.751 to 0.836). This supports the value placed on AIoT components in defining this construct similarly. The results of the proposed model show that Big Data Analytics and Artificial Intelligence → Green Digital Learning (GDL) has a significant path coefficient of 0.636, which essentially means that progress in big data analytics and AI significantly influences digital learning capabilities in a green or sustainable manner. This, in turn, underscores how data and AI techniques can assist in promoting sustainable digital education endeavors. It can be safely stated regarding Hypothesis (1) that Green Digital Learning does play a significant role in Green Supply Chain Performance (GSCP) with a path coefficient of 0.676 (Table 10). It suggests that efficient and durable digital learning practices have a positive impact on the performance of environmentally friendly or green supply chain activities. This would draw an important link between knowledge circulated through digital methods of learning and sustainable practices in the supply chain domain. One of the most interesting findings by comparing the direct impacts among them is that Big Data & Artificial Intelligence can only influence Green Supply Chain Performance with a path coefficient of 0.004, see Figure 10a. This probably indicates that green digital learning only establishes a mediated channel between big data analytics and AI of green practices and its effect on green supply chain outcomes, instead of directly receiving or exerting the same effects. Last but not least, although the impact of the integration of Artificial Intelligence of Things on green digital learning is relatively small (0.096), it has a greater effect on green supply chain performance (0.559).

This direct relation emphasizes the ability of AIoT technologies to positively impact green supply chain performance, such as streamlining operations and enhancing resource efficiency in real-time [19]. Thus, this model demonstrates a complicated interrelationship where Big Data Analytics, Artificial Intelligence, and the Integration of AIoT improve Green Supply Chain Performance through both direct and indirect routes via Green Digital Learning. The path model highlights the linkage between digital, AI-driven, and IoT-based innovations to direct the benefits of these practices towards achieving sustainability in supply chain settings (SCS).

6.2. AVE and Reliability

For variable reliability analysis, Table 1 provides the primary reliability measures and tests of validity for four constructs in the study, including Big Data Analytics and Artificial Intelligence, Green Digital Learning, Green Supply Chain Performance, and Integration of Artificial Intelligence of Things. This table shows the values of Cronbach's alpha, Composite Reliability (rho_a and rho_c), and Average Variance Extracted (AVE) per construct. These measures are key to determining the internal consistency, reliability, and convergent validity of the model constructs.

Table 1.
Reliability and testing of AVE.

Vs	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Big data analytics and artificial intelligence	0.852	0.862	0.894	0.628
Green digital learning	0.890	0.894	0.917	0.650
Green supply chain performance	0.910	0.911	0.929	0.651
Integration of artificial intelligence of things	0.867	0.874	0.904	0.653

As is shown in Table 1, reliability and validity statistics are very high in each of these constructs (Cronbach's alphas all > 0.80; AVIF = 1.00), with good support for both pattern convergent validity and discriminant validity. All constructs have Cronbach's alpha greater than 0.85, which suggests excellent internal consistency among the items within each construct. Given this high alpha value, it follows that each of these constructs provides a relatively error-free measure (defined as low random variance) of the underlying concept. Additionally, Composite Reliability (rho_a and rho_c) values are high for all constructs, ranging from 0.862 to 0.929. Most authors believe that CR is a better measure of the reliability of a construct than Cronbach's alpha, especially for structural equation models. Its high rho_a and rho_c values provide evidence that each construct captures the concept of interest consistently across all items and can thus be interpreted as being consistent in capturing the attribute associated with each construct. AVE values for all the constructs are greater than the threshold of 0.50, measuring between 0.628 and 0.653, respectively. If the AVE value is greater than 0.50, this suggests that the construct explains more than half of the variance in items and hence provides strong evidence for convergent validity. This confirms that the indicators are (highly) correlated with their single construct, which is an essential feature in establishing the construct validity in the model.

In Table 2, R^2 and Adjusted R^2 Values Results, two constructs in the model illustrate green digital learning values of R-square and adjusted R-square and green supply chain performance. This indicates the form of variance in each dependent construct explained by its predictors, with adjusted R-square accounting for the number of predictors in the model to predict an accurate value for model fit.

Table 2.
R^2 and adjusted R^2 values results.

DV	R-square	R-square adjusted
Green digital learning	0.404	0.402
Green supply chain performance	0.559	0.554

Based on Table 2, the R-squared of Green Digital Learning is 0.404, suggesting that around 40.4% of the variation in this construct can be predicted by its predictors. The adjusted R-squared value of 0.402 reveals that the model can explain only part of the variance in Green Digital Learning, but it is still better than the raw R-squared considering its large number of predictor variables. The moderate R-squared value suggests that the model's predictors are influential, but other factors affecting Green Digital Learning were not accounted for. The R-squared, with Green Supply Chain Performance as a dependent variable, is relatively higher at 0.559; the value of the adjusted R-squared is 0.554 (see Table 2). This means the model accounts for roughly 55.9% of the variance in Green Supply Chain Performance; therefore, we can say that the predictors included in this model explain a sizeable amount of variance for this construct. A small discrepancy between the R-squared and adjusted R-squared suggests that the model is appropriately specified without overfitting.

6.3. Hypotheses Testing and Structural Model

Analysis of hypotheses in the structural model is designed to examine the extent to which constructs predicted by the developed conceptual framework are a reality. The first approach allows researchers to estimate and test for significant path coefficients representing hypothesized relationships between constructs. The model also tests the relationships of “Big Data Analytics and Artificial Intelligence,” “Integration of Artificial Intelligence of Things,” and “Green Digital Learning” with “Green Supply Chain Performance.” Each of these path coefficients specifies how strongly one construct really affects the other. It outputs not only the coefficients of the model but also statistical significance values indicating whether these relationships are significant given what we know about our predictor variables. Figure 3 shows the Structural Model and the proposed relationships among constructs with their respective path coefficients. Central nodes represent each construct, while paths between nodes reflect the relationships tested in the model. Figure 3 arrows point from constructs to each of the individual indicators, and loadings for each term are noted in parentheses next to it, with p-values at the end, denoted as a significance level of each relationship.

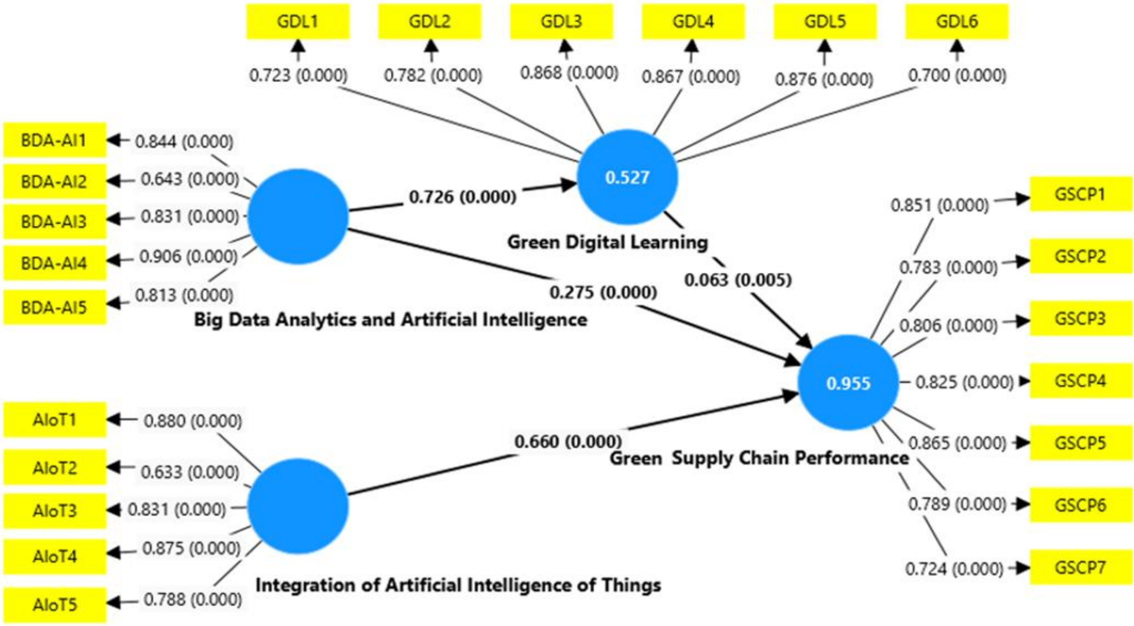

Figure 3.
Hypothesis testing results.

The structural model shows how the constructs are related, and each path coefficient indicates the strength of the relationship from one construct to another. These factor loadings for Big Data Analytics and Artificial Intelligence (BDA-AI) ranged from 0.643 to 0.906, all of which were statistically significant at 0.000, hence indicating internal reliability and a very strong contribution toward the overall construct of eco-efficient asset management practices (Table 4). Reasonable goodness of fit: GFI = 0.934, AGFI = 0.830. The minimal partial estimate (MPR) indicates that BDA-AI directly influences Green Digital Learning (GDL) with a path coefficient of 0.726 and a significant effect with a p-value of 0.000. Through this route, it can be inferred that BDA-AI on GDL has a perfectly good impact. Hence, advances in big data analytics and AI do increase sustainable DLE to a far greater extent. Similarly, AIoT (Artificial Intelligence of Things) has high factor loadings across its indicators as well (between 0.633 and 0.880), and is also highly significant with p-values of 0.000. The effect of AIoT on Green Supply Chain Performance (GSCP) shows a direct path coefficient of 0.660 ($p = 0.000$). Thus, the signs of regression results are positive and statistically significant, which means that the integration of AIoT is expected to directly enhance green supply chain performance, thereby reducing resource waste and improving environmental efficiency. The direct effect coefficient of Green Digital Learning on Green Supply Chain Performance is found to be moderate and significant, with a path coefficient of 0.063 and $P = 0.005$, as presented in Table 3. While the relationships are weaker than those where AIoT conditions were directly predicted, these findings suggest that sustainable learning practices also have some effect on improving green supply chain performance. The results obtained via the structural path analysis that explains direct relationships among constructs are provided in Table 4 as "Results of the Structural Model." Each row signifies a relationship and displays the original sample path coefficient (O), the sample mean (M), the standard deviation (STDEV), t-statistic, and p-value. With the aid of these values, the strength, consistency, and statistical significance of every hypothesized path can be assessed, thus allowing us to validate or reject each hypothesized direct effect in the model.

Table 3.
Results of the structural model.

Vs	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Big Data Analytics and Artificial Intelligence -> Green Digital Learning	0.726	0.726	0.036	19.974	0.000
Big Data Analytics and Artificial Intelligence -> Green Supply Chain Performance	0.275	0.275	0.052	5.286	0.000
Green Digital Learning -> Green Supply Chain Performance	0.063	0.063	0.022	2.808	0.005
Integration of Artificial Intelligence of Things -> Green Supply Chain Performance	0.660	0.661	0.055	11.929	0.000

The results in Table 4 reveal significant relationships among the constructs in the model. The relationship between Big Data Analytics, Artificial Intelligence, and Green Digital Learning is particularly strong, with a path coefficient of 0.726 and a t-statistic of 19.974 ($p = 0.000$), indicating a highly significant positive influence. This suggests that advancements in big data analytics and AI are essential for enhancing green digital learning capabilities. Similarly, the relationship between Big Data Analytics, Artificial Intelligence, and Green Supply Chain Performance (path coefficient of 0.275, p = 0.000) is also significant, though weaker in comparison, indicating that BDA-AI contributes positively to green supply chain outcomes. Additionally, Green Digital Learning has a moderate impact on Green Supply Chain Performance (0.063, p = 0.005), highlighting that green digital learning directly supports sustainable supply chain practices, though to a lesser extent. Finally, the path from the Integration of Artificial Intelligence of Things (AIoT) to Green Supply Chain Performance is strong, with a coefficient of 0.660 (p = 0.000), signifying that AIoT integration plays a vital role in achieving sustainability in supply chain operations. Overall, these results underscore the importance of digital and AI-driven solutions in fostering green initiatives within the supply chain context. However, Table 4 also provides insights into the indirect effects within the structural model, focusing on the mediating role of Green Digital Learning between Big Data Analytics, Artificial Intelligence, and Green Supply Chain Performance. The table includes the original sample path coefficient (O), sample mean (M), standard deviation (STDEV), t-statistic, and p-value for the indirect effect, indicating whether the mediating pathway is statistically significant.

Table 4.
Result of mediation effect.

Mediation	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Big Data Analytics and Artificial Intelligence -> Green Supply Chain Performance	0.046	0.045	0.016	2.782	0.005

Based on the above Table 4, the results of the mediation analysis demonstrate a significant indirect effect of Big Data Analytics and Artificial Intelligence on Green Supply Chain Performance through Green Digital Learning, with an indirect path coefficient b = 0.046, t-statistic = 2.782 (p = 0.005). This result implies that the impact of Big Data Analytics and Artificial Intelligence on Green Supply Chain Performance is mediated by Green Digital Learning only partially. This mediation effect suggests that BDA-AI improvements result in better green supply chain outcomes, both directly and indirectly, by strengthening green digital learning capabilities. This mediation result illustrates how green digital learning is complementary in further enhancing the positive effects of data and AI-driven strategies on sustainable supply chain performance. More specifically, it indicates that the benefits of big data and AI in realizing green supply chains can be significantly enhanced by fostering digital learning initiatives towards modern sustainability goals. By adopting this layered sustainable development model, it is clear that we need to invest serious time in researching how learning frameworks and technologically advanced systems can work holistically to achieve the greenest outcomes from our supply chain efforts.

7. Discussion

The results of the study can be beneficial in understanding some relationships among Big Data Analytics and Artificial Intelligence (BDA-AI), Artificial Intelligence of Things (AIoT), Green Digital Learning, as well as Green Supply Chain Performance (GSCP). This complements and, in some cases, adds to existing research on green supply chain management. Every hypothesis and main effect is scrutinized in the context of related studies to help understand these results throughout the field. In addition, Green supply chain processes: Similarly, a positive and significant direct path coefficient of 0.275 (t-statistic = 5.286, p-value = 0.000) illustrates the effectiveness of advanced analytics and AI in GSCP optimization due to BDA-AI. This result is consistent with the notion in earlier research that BDA-AI can enable improved environmental performance through predictive analytics and data-based decision-making [1, 2]. The impact on GSCP reveals the effectiveness of BDA-AI technologies in reducing waste, increasing operational efficiency, and facilitating organizations to respond swiftly to environmental challenges, which are crucial for maintaining market competitiveness and being compliant with sustainability targets.

But this study also suggests that the impact of BDA-AI on GSCP is somewhat less compared to its effect on Green Digital Learning (the path coefficient = 0.726). This contrast underscores a disconnect between the transformative potential of BDA-AI and the actual value generation on green supply chains, implying that other components, such as learning environments designed to catalyze and animate these technologies in practice, have been overlooked, which determines a more accurate estimation of their full environmental consequences because of their exertions. First, the robust effect of AIoT on GSCP (path coefficient = 0.660; t-statistic = 11.929; p-value = 0.000) suggests that the implementation of IoT equipped with AI is an effective critical intervention to foster sustainability in supply chain operations (SCOs). It is in line with the literature that AIoT acts as a disruptive technology that can lead to improved real-time resource utilization and cost efficiency due to predictive analytics and automated decision-making [16] learning [17].

Being intelligent, the system created by AIoT can adapt to supply chain conditions and adjust itself dynamically to reduce resource consumption effectively and minimize environmental impact. The current study enriches the available literature by its ability to quantify the effects of AIoT on the GSCP and establish it as a major contributing factor to sustainability in supply chains. However, it also highlights some of the key implementation barriers, ranging from high costs to stringent regulatory requirements [2] that may restrict widescale uptake. These findings indicate that, while AIoT is promising for sustainable supply chains, much work remains to be done in developing strategic frameworks for the design of AIoT and navigating the operational and regulatory hurdles of its deployment.

Findings: The results demonstrate a statistically and theoretically significant moderating role of Green Digital Learning for the path BDA-AI and through mediation between GSCP, with an indirect path coefficient of 0.046 (t-statistics = 2.782, p-value = 0.005). It is clear from this result that Green Digital Learning (path coefficient = 0.063) has both its independent effect and strengthens the role of BDA-AI in influencing green supply chain outcomes. This observation is consistent with Benzidia, et al. [1] and Feng, et al. [7], who point out that online learning provides employees with the ability to correctly interpret and act on data-based insights, generating positive changes with long-lasting, continuous improvement practices. Manuscript Title: The impact of digital learning maturity on green supply chains: A critical role of Green Digital Learning. In doing so, they can achieve the maximum environmental benefit of their BDA-AI insights on GSCP by also developing a skilled workforce that can specifically leverage those insights for environmental goals. Despite its potential benefits, barriers such as resource constraints and organizational resistance to change [2] can hinder the achievement of wide adoption of GDL.

In their study, the mediation effect of this research establishes the importance of investing in sustainable digital training that indirectly supports both a pathway and an enabler to properly leverage sustainability benefits with BDA-AI technologies. These findings, taken together, highlight the importance of new technologies and e-learning for improving the performance of green supply chains. The main drivers impacting GSCoP were BDA-AI and AIoT, which have emerged as a dominant force with their potential for real-time, adaptive supply chain management. The results were also supported by previous studies that underline the opportunity of AIoT for sustainability [10, 16, 17]. Moreover, the results substantiate that Green Digital Learning is positioning itself as a moderator, strengthening the relationship between BDA-AI and GSCP. This demonstrates a moderate mediation effect and suggests that environmental performance hinging on technology may fail unless there is a simultaneous focus on building the capabilities of employees to fully utilize these tech tools for sustainability.

8. Conclusion

The findings of the study serve to add value to the ongoing research publications on sustainable supply chain management, which will be supported with empirical evidence concerning developing and deploying emerging digital technologies while facilitating employee learning. The synergy between BDA-AI, AIoT, and Green Digital Learning shapes an end-to-end climate-friendly journey that organizations can adopt in the pursuit of balancing competitive edge with sustainability. In a wider context, future research should focus on the practical barriers in implementing AI-based digital learning (AIoT) and strategies to overcome these issues, especially in resource-constrained settings. Moreover, exploring mixed industrial contexts may illuminate further how these technologies have differential impacts in crafting customized green supply chain strategies. Based on the findings, it is concluded that BDA-AI and AIoT are two indispensable armors for superior-level renewed green supply chain success while there must be a lot of digitally skilled workforce backed by Green Digital Learning. With that in mind, organizations are going to have to take a holistic stance toward technology innovation and employee empowerment if they are truly going to drive sustainable supply chain practices. Therefore, this paper offers noteworthy implications on the utilization of Big Data Analytics (BDA) and Artificial Intelligence (AI), Artificial Internet of Things (AIoT), and Green Digital Learning for supporting sustainability/gender aspects in improving Green Supply Chain Performance. The results reveal the key roles of BDA-AI and AIoT in improving process integration into environmental and market competitiveness, as well as the important impact moderation of Green Digital Learning. The response of GSCP to AIoT has been particularly instrumental in achieving this ability for real-time, adaptive supply chain management that is so closely aligned with sustainability goals (resource utilization and ecological footprint reduction). In parallel, Green Digital Learning enhances GSCP directly and provides an essential enabler to help our employees use BDA-AI insights in the right way: translating technological promise into business value. The insights of this study are able to explain how digital innovations can advance sustainable supply chain practices with the support of a focused learning program. This emphasizes the need to dual-invest not only in advanced technologies but also in organizational learning frameworks that can be used together to maximize digital tools for environmental benefits. With the push toward truly green supply chain solutions firmly on the global agenda, companies should understand that simply utilizing new technology will not mean they meet green supply chain goals. It takes a holistic strategy that prepares people with the competencies to translate technological trends for sustainable goals. Finally, the major areas for future research are to probe into effective and efficient techniques for implementing AIoT and Green Digital Learning among resource-constrained settings, as well as to focus carefully on such factors in different industrial sectors. This will better enable organizations to navigate the complexities surrounding green supply chains and, in doing so, gain a competitive advantage as well as create positive change for all stakeholders within a more sustainable global economy.

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