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Towards Sustainable IT Infrastructure: Integrating Green Computing with Data Warehouse and Big Data Technologies to Enhance Efficiency and Environmental Responsibility

Jennifer Chinelo Ugonnia [a++], Oluwaseun Oladeji Olaniyi [b#*], Folashade Gloria Olaniyi [c†], Abiodun Aliyah Arigbabu [d‡], Tunbosun Oyewale Oladoyinbo [e^]

[a] Ulster University, Centre City House, 7 Hill St, Birmingham B5 4UA, United Kingdom.
[b] University of the Cumberlands, 104 Maple Drive, Williamsburg, KY 40769, United States of America.
[c] University of the People, 595 E Colorado Blvd Suite 623, Pasadena, CA 91101, United States of America.
[d] Tai Solarin University of Education, Ijebu-Ode, Ogun State, Nigeria.
[e] University of Maryland Global Campus, 3501 University Blvd E, Adelphi, MD 20783, USA.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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++ Technology, Business, and Hospitality Research Expert;
 # Information Technology Researcher;
† Cyber security and Data Expert;
‡ Computer Science, Business Intelligence, Cloud and Data Security;
^ Principal, Cybersecurity Analyst/ Researcher;
**Corresponding author: Email: oolaniyi00983@ucumberlands.edu;*

ABSTRACT

This research examines the integration of green computing practices within data warehousing and big data technologies, focusing on their effects on organizational efficiency and environmental responsibility. The increasing reliance on information technology in business operations has led to significant environmental implications, including increased energy consumption and carbon emissions. This study explores how sustainable IT practices, specifically green computing, can be effectively integrated with data warehouses and big data technologies to address these challenges. A quantitative research methodology was employed, utilizing a structured questionnaire distributed among 389 IT professionals selected through purposive sampling. The data collected were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) to identify relationships between green computing integration, energy consumption, carbon emissions, and operational efficiency. Findings from the study indicate a significant negative relationship between green computing practices and energy consumption and emissions, suggesting that integrating green computing can substantially reduce environmental impacts. Moreover, a positive correlation was found between green computing integration and operational efficiency, highlighting the operational benefits of sustainable IT practices. Despite potential challenges such as initial costs and expertise requirements, the benefits of integrating green computing within data warehousing and big data technologies are clear, offering pathways to enhanced sustainability and efficiency. The study concludes that adopting green computing practices is a strategic move towards environmental responsibility and a means to achieve operational improvements and cost savings. Recommendations include developing comprehensive green computing strategies, investing in energy-efficient technologies, enhancing employee expertise in sustainable practices, and continuously monitoring and optimizing IT infrastructures for sustainability.

Keywords: Green computing; data warehousing; big data technologies; sustainable IT practices; energy consumption; carbon emissions; operational efficiency; environmental sustainability.

1. INTRODUCTION

The digitization of business operations and the increasing reliance on information technology (IT) have become hallmarks of the modern competitive business environment. As organizations strive for efficiency, innovation, and market dominance, adopting and integrating emerging technologies have become pivotal [1]. Among these, data warehouses and big data technologies stand out for their capability to handle vast amounts of data, enabling enhanced decision-making, strategic planning, and operational efficiencies [2,3]. However, this surge in data-centric technologies comes with significant environmental implications, primarily due to the substantial energy consumption and carbon emissions associated with powering, cooling, and maintaining IT infrastructures [4,5]. The importance of addressing these environmental impacts cannot be overstated, as the IT sector's carbon footprint has grown to rival that of entire countries, making the pursuit of sustainable IT practices an urgent global concern [4].

Within this broader context of IT's environmental impact, the focus narrows to the intersection of green computing, data warehouses, and big data technologies. Green computing emerges as a critical response to the environmental challenges the IT sector poses, advocating for energy-efficient computers, servers, and data centers, alongside reduced resource consumption and minimized waste [6]. The role of data warehouses and big data technologies is particularly pertinent due to their extensive energy use and the potential for significant environmental impacts [7,8]. Despite the recognized need for sustainable practices, integrating green computing with these technologies still needs to be explored and utilized in organizational IT strategies. This gap highlights a critical area of research: how can organizations effectively integrate green computing with data warehouse and big data technologies to enhance efficiency and decision-making capabilities and contribute to environmental sustainability? Addressing this question is vital for developing IT infrastructures supporting business competitiveness while fulfilling environmental and social responsibilities. This study aims to delve into this integration, exploring its implications for energy consumption, operational efficiency, and environmental stewardship in the context of sustainable IT infrastructure development. Hence, the study explores integrating green computing practices with data warehouses and big data technologies to enhance organizational efficiency and environmental responsibility within sustainable IT infrastructure development.

1.1 Research Objectives;

1. To investigate the current state and challenges of implementing green computing practices in data centers and IT infrastructure to reduce carbon emissions and energy consumption.
2. Analyze the architectural frameworks and components of data warehouses and big data technologies to identify opportunities for energy efficiency and sustainability improvements.
3. Examine case studies or examples of successful integration of green computing with data warehousing and big data technologies, focusing on the outcomes related to environmental impact and operational efficiency.
4. Propose a set of best practices and guidelines for organizations seeking to adopt green computing strategies within their data warehouse and big data infrastructures to promote sustainability and reduce environmental footprint.

1.2 Research Hypotheses:

H_1 Organizations that integrate green computing practices with their data warehouse and big data technologies experience a significant reduction in energy consumption and carbon emissions compared to those that do not.

H_2 The implementation of energy-efficient architectural frameworks and components in data warehouses significantly enhances the overall sustainability of IT infrastructure.

H_3 There is a positive correlation between the level of integration of green computing practices in data warehousing and big data technologies and the operational efficiency of organizations.

H_4 Adopting green computing guidelines and best practices leads to improved environmental responsibility and contributes to the long-term sustainability of IT infrastructure.

2. LITERATURE REVIEW

The synthesis of existing literature reveals a consensus on the urgency to adopt environmentally sustainable IT practices amidst the digital data deluge, with green computing emerging as a critical enabler of reduced energy consumption and lower carbon footprints in data-intensive operations [8]. However, controversies persist regarding the implementation complexities, cost implications, and scalability of green computing solutions within data warehousing and big data technologies [9].

2.1 Data Warehousing

Data warehousing, a cornerstone of modern business intelligence, has revolutionized how organizations manage, store, and analyze data [10]. In response to the competitive business environment, data warehousing has evolved from simple data storage solutions to complex systems that handle vast amounts of structured and unstructured data [11,12]. This evolution is driven by the need for organizations to adopt enduring IT strategies that incorporate emerging technologies for sustainability and competitive advantage [13,14,15]. Integrating data warehousing with big data technologies signifies a pivotal shift, enabling enhanced decision-making and strategic planning while raising concerns about the environmental impact due to their significant energy consumption and carbon emissions [16,17].

2.2 Architecture and Components of Data Warehouses

The architecture of a data warehouse is designed to support the extensive data analytics capabilities required by modern enterprises, surpassing the limitations of traditional database systems [18,19]. This architecture, typically structured in a three-tier model, facilitates data's efficient transmission, processing, and presentation [18]. The bottom tier focuses on data collection and conversion through an ETL (Extraction, Transformation, and Loading) process, the middle tier offers online analytical processing for rapid data queries, and the top tier provides the user interface for data analysis [20]. Essential components of this architecture include the data warehouse database, ETL tools, data access tools, metadata, data warehouse bus, and the reporting layer [20]. Each component is crucial in ensuring the data warehouse's functionality, from data storage and management to analysis and reporting [20].

2.3 Types of Data Transformations in Data Warehousing

Data transformation is critical in preparing data for a data warehouse, addressing the challenges posed by raw data's unreliability and inconsistency [21]. This process involves several stages: data assessment, ingestion, cleansing, formatting, combination, and analysis [21,22]. These stages are designed to refine the data, ensuring its accuracy, consistency, and compatibility with the data warehouse structure [23]. Through data transformation, organizations can leverage advanced business intelligence tools to generate insightful performance reports and forecast trends [23,24,25]. The meticulous data transformation process underscores the importance of data quality in achieving reliable analytics and decision-making outcomes [25].

2.4 Current Trends in Data Management Warehousing

Data warehousing continually evolves, with current trends shifting towards more flexible, scalable, and efficient data management solutions [26]. The development of data lakes and lakehouses represents a significant trend, offering a more adaptable and cost-effective approach to managing large data volumes [26,27]. Data lakes serve as centralized repositories for all types of organizational data, supporting diverse analytics and decision-making needs [28]. Lakehouses combine the benefits of data lakes and traditional data warehouses, providing a unified platform for data storage, management, and analysis [28,29]. These trends reflect the growing need for innovative data structures that can accommodate the expanding scope of data collection while supporting the democratization of data for enhanced safety, governance, and compliance [30]. The shift towards data lakes and lakehouses illustrates the ongoing transformation in data warehousing practices, driven by the demands of extensive data management and the pursuit of operational efficiency and sustainability [30].

2.5 Big Data

Big Data encompasses vast volumes of structured, semi-structured, and unstructured data inundating businesses daily, challenging traditional data processing tools with complexity and scale [31]. This data, characterized by its variety, volume, veracity, velocity, and value, has become a critical asset for organizational competitiveness and innovation [32,33]. Unlike traditional datasets, big data's significance transcends its size, emphasizing its utility in extracting insights, trends, and patterns that inform strategic decisions and problem-solving within organizations [34,35,36]. The effective management and analysis of big data rely on a sophisticated technological infrastructure encompassing data storage solutions, cluster computing systems, extensive networks, sensors, advanced data analytics algorithms, and cloud computing facilities [34]. These technologies facilitate the processing and analysis of big data, enabling organizations to derive meaningful insights that drive performance, innovation, and sustainability [32]. Integrating these technologies is essential for harnessing the full potential of big data, underscoring the need for robust and scalable IT infrastructures that can accommodate the demands of big data analytics [32,28].

2.6 Demands and Impact of Big Data on Organizations

Big data has revolutionized the business landscape, offering unprecedented opportunities for enhancing decision-making, strategic planning, and operational efficiencies [36]. It empowers organizations to refine their business strategies, discover key market insights, innovate products and services, and achieve a competitive edge through in-depth, rapid analysis [37,38]. Furthermore, big data analytics enables small and emerging enterprises to overcome market entry barriers, optimize pricing strategies, improve customer engagement, and tailor marketing initiatives to specific demographics, ultimately driving growth and sustainability [34,37,38].

The surge in big data's role within organizational operations brings to light significant environmental concerns, notably the substantial energy consumption and carbon emissions associated with the IT infrastructure required to store, process, and analyze this data [31,39]. The environmental footprint of big data underscores the urgency for integrating green computing practices within data management technologies to mitigate the adverse impacts on the environment [39,40]. As organizations strive to leverage the advantages of big data, it is imperative to consider sustainable IT strategies that align with environmental stewardship while maintaining operational efficiency and competitive advantage.

2.7 Green Computing

Green computing focuses on environmentally sustainable computing or IT practices. It involves designing, manufacturing, using, and disposing of computers, servers, and associated subsystems—such as monitors, printers, storage devices, and networking and communications systems—efficiently and effectively with minimal or no environmental impact [41,42]. The primary objectives of green computing include reducing energy consumption, minimizing electronic waste, and lowering greenhouse gas emissions, thereby addressing the environmental impacts of digital operations [43]. The information and communication technology (ICT) sector is a significant energy consumer and carbon emitter, contributing to global greenhouse gas emissions and necessitating the shift towards more sustainable practices [43,44].

2.8 Strategies for Implementation of Green Computing

To mitigate the environmental footprint of IT and extensive data operations, several strategies can be employed to make data centers and computing practices more sustainable [43,45]. By allowing multiple virtual servers to run on a single physical server, server virtualization significantly reduces the need for physical hardware, leading to lower energy consumption and reduced space requirements [46]. This approach not only cuts down on the energy used for cooling but also decreases the overall electrical demand of data centers [47,48]. Jin et al. [44] suggest that organizations should consider configuring data centers with hot and cold aisles to optimize the effectiveness of cooling systems by managing the air flow more efficiently. This setup helps reduce energy consumption and associated costs, reducing IT operations' carbon footprint [44]. In addition, implementing policies for powering down non-essential equipment when not in use can lead to substantial energy savings. This simple yet effective strategy ensures that only necessary devices consume power, reducing energy demand [47].

According to IBM [43], transitioning to renewable energy sources for powering data centers and IT infrastructures is crucial for sustainability. Investments in solar, wind, and hydroelectric power can replace reliance on fossil fuels, reducing carbon emissions and promoting renewable energy use within the sector [48,49]. Prioritizing the purchase of devices designed for energy efficiency can significantly reduce the energy consumption of IT operations; thus, opting for laptops over desktop computers, for example, can contribute to this goal by leveraging these devices' inherently lower energy demand [50]. Intel's initiatives in green computing illustrate the practical application and benefits of adopting sustainable IT practices. By rethinking server architecture and operations, Intel significantly reduced energy consumption and electronic waste [17,51]. The company's approach to modular server design allows for the selective upgrade of components, reducing the need for complete system replacements and thus minimizing waste. Furthermore, Intel's focus on improving power use effectiveness (PUE) and investing in renewable energy sources underscores the potential for industry-wide impact through committed green computing practices [17].

2.9 Integrating Green Computing with Data Warehousing and Big Data: Challenges and Opportunities

The potential for sustainability through integrating green computing with data warehousing and big data technologies is immense. Green computing practices, aimed at reducing energy consumption and minimizing environmental impacts, align with the growing need for more sustainable data management solutions [49,51]. For instance, transitioning to energy-efficient servers and storage solutions, optimizing data processing algorithms for reduced energy use, and adopting cloud-based data warehousing solutions can drastically lower the carbon footprint of data management operations [52]. These measures directly address the environmental concerns associated with the massive energy consumption and heat generation of traditional data centers, contributing to carbon emissions and significant electronic waste [53].

According to Boiko et al. [54] and Attaran et al. [31], one of the primary challenges in this integration is the inherent energy intensity of data warehousing and extensive data operations, as the storage, processing, and analysis of large datasets demand substantial computational resources and, consequently, significant energy consumption; whereas, the existing infrastructure for many organizations is not designed with energy efficiency in mind, posing a barrier to the adoption of green computing principles. Retrofitting these systems to incorporate energy-efficient technologies and practices can entail considerable expenses and operational disruptions, making it a daunting task for many enterprises [54]. In addition, as data volumes continue to grow exponentially, ensuring that green computing practices can scale effectively to meet these demands is critical; thus, the scalability issue is not just a technical challenge but also a strategic one, requiring ongoing investment in innovative technologies and methodologies that can adapt to the evolving nature of data warehousing and big data [51,53].

Despite these challenges, integrating green computing with data warehousing and big data technologies offers substantial opportunities, such as operational cost savings, considering that energy-efficient practices and technologies can reduce the energy consumption of data centers, leading to lower utility costs [55]. Moreover, adopting renewable energy sources and optimizing data center designs for better energy use can contribute to long-term financial savings, offsetting the initial investments required for green computing integration [56]. Innovative green computing technologies also present opportunities for enhancing system performance and reliability. For instance, server virtualization reduces energy consumption and increases the flexibility and efficiency of data storage and processing operations. Similarly, using advanced cooling technologies and energy management systems can improve the overall efficiency of data centers, reducing operational costs and minimizing the environmental impact [36,56].

The integration of green computing practices offers a pathway to corporate social responsibility (CSR) and sustainable business practices, and organizations that successfully incorporate these practices into their data management strategies can bolster their reputation as environmentally responsible entities [57]. This reputation can, in turn, enhance customer loyalty, attract ecologically conscious investors, and comply with regulatory requirements for sustainability and environmental protection [57,58]. Furthermore, the drive towards green computing stimulates innovation in data management technologies, considering that the need for energy-efficient solutions spurs the development of new hardware, software, and methodologies that prioritize sustainability without compromising on performance or scalability [59]. These innovations can give early adopters a competitive edge, showcasing how environmental sustainability and business efficiency can go hand in hand.

2.10 The case of Apple's Maiden Data Center

Apple's data center in Maiden, North Carolina, demonstrates how green computing principles can seamlessly integrate with data warehousing and big data technologies to achieve operational excellence and environmental leadership [60]. At the heart of Apple's green approach lies an unwavering commitment to renewable energy with its data center powered by 100% clean energy, a feat accomplished through a two-pronged strategy - a vast solar panel installation blanketing the campus harnessing the power of the sun, generating a substantial portion of the facility's electricity needs, and renewable energy credits (RECs) procured from external sources to supplement on-site generation and ensure complete reliance on renewables, thus, Apple offsets the remaining energy consumption [61]. This provides the data center's operations with no trace of fossil fuel dependence, minimizing its impact on climate change.

The company also leverages high-performance building materials that boast superior thermal insulation, reducing the need for energy-intensive heating and cooling systems, with strategically placed vents and airflow management systems to leverage the power of natural ventilation whenever possible, further minimizing reliance on mechanical cooling [61].

In addition, Apple ingeniously leverages data warehouse and big data technologies to optimize energy consumption and resource allocation within the data center [61,62]. Sensors and meters scattered throughout the facility gather real-time energy usage data stored in a central data warehouse [62]. By analyzing this data, Apple can pinpoint areas for improvement and implement targeted strategies to enhance efficiency [62]. Big data analytics are crucial in predictive maintenance, allowing the company to anticipate equipment failures and optimize maintenance schedules. This proactive approach prevents downtime and ensures peak efficiency for all systems, minimizing energy waste [62]. Data warehouse and extensive data capabilities are also harnessed to optimize server workload distribution. This ensures that resources are allocated efficiently, reducing the need for additional servers and minimizing overall energy consumption. In light of environmental impact, Apple's facility reliance on renewable energy sources and water-efficient technologies translates to a significantly reduced environmental footprint, as in 2021 alone, projects supporting the Maiden data center prevented over 171,000 metric tons of CO2e emissions [61,62].

3. METHODS

This study used quantitative methods to examine how green computing practices can be integrated within data warehousing and big data technologies to boost organizational efficiency and environmental responsibility. A survey strategy was employed to collect the data, using questionnaires as the primary data research instrument. The respondents were IT specialists recruited through a purposive sampling technique, considering their direct engagement with or knowledge of operational aspects of data centers and related technologies. The researchers leveraged their professional networks and industry connections to engage a diverse group of participants, culminating in responses from 389 IT professionals. Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed to analyze the gathered data and test the hypotheses proposed. This choice was motivated by PLS-SEM's effectiveness in exploring complex variable relationships and its suitability for hypothesis testing within the study's framework. In conducting this research, ethical considerations were paramount. The confidentiality and anonymity of the survey respondents were rigorously protected, with participants fully briefed on the study's objectives, their participation's voluntary nature, and the measures in place to safeguard their information.

4. RESULTS

The result from the Measurement Model Analysis focusing on Convergent Validity presents an in-depth examination of the constructs within the study: Green Computing Integration (GCI), Energy Consumption & Emissions (ECE), and Operational Efficiency (OE). For each construct, various indicators were analyzed in terms of item loading and item community, along with the assessment of Cronbach's Alpha, Composite Reliability, and Average Variance Extracted (AVE).

In the Green Computing Integration (GCI) context, three indicators (GCI1, GCI2, and GCI3) were evaluated. The item loadings for these indicators showed intense levels, ranging from 0.79 to 0.84, suggesting a robust relationship between the indicators and the construct. Item communality values, which reflect the proportion of variance captured by the construct from each indicator, ranged from 0.62 to 0.71, indicating a satisfactory level of shared variance. The construct demonstrated excellent reliability and internal consistency, with a Cronbach's Alpha of 0.88 and a Composite Reliability of 0.90. The AVE for GCI was 0.64, surpassing the recommended threshold of 0.50, which confirms a good level of convergent validity.

For Energy Consumption & Emissions (ECE), two indicators (ECE1 and ECE2) were scrutinized. Item loadings were robust, with values of 0.83 and 0.86, respectively, indicating a strong association with the construct. The item communality values were also high, at 0.69 and 0.74, demonstrating a significant portion of variance captured by the construct. The reliability measures were impressive, with a Cronbach's Alpha of 0.91 and a Composite Reliability of 0.92. The AVE for ECE stood at 0.68, further attesting to the construct's convergent validity.

Operational Efficiency (OE) was examined through two indicators (OE1 and OE2), with item

Table 1. Measurement Model Analysis (Convergent Validity)

Constructs	Indicators	Item Loadings	Item Communality	Cronbach's Alpha	Composite Reliability	AVE
Green Computing Integration (GCI)	GCI1	0.81	0.66	0.88	0.90	0.64
	GCI2	0.84	0.71			
	GCI3	0.79	0.62			
Energy Consumption & Emissions (ECE)	ECE1	0.83	0.69	0.91	0.92	0.68
	ECE2	0.86	0.74			
Operational Efficiency (OE)	OE1	0.80	0.64	0.89	0.91	0.65
	OE2	0.82	0.67			

loadings of 0.80 and 0.82, respectively. These values signify a strong linkage between the indicators and the OE construct. The item communality values for OE1 and OE2 were 0.64 and 0.67, indicating a good level of variance accounted for by the construct. The construct's reliability is highlighted by a Cronbach's Alpha of 0.89 and a Composite Reliability of 0.91. With an AVE of 0.65, the OE construct also meets the criteria for convergent validity. Overall, the results from the Measurement Model Analysis demonstrate that the constructs and their respective indicators exhibit strong item loadings, satisfactory item commonality, and excellent reliability and validity measures. This suggests that the constructs of Green Computing Integration, Energy Consumption & Emissions, and Operational Efficiency are well-defined, reliable, and valid within the context of this study.

The result from the Discriminant Validity analysis using the Fornell-Larcker Criterion reveals how distinct the constructs of Green Computing Integration (GCI), Energy Consumption & Emissions (ECE), and Operational Efficiency (OE) are from one another within the study. The Average Variance Extracted (AVE) values reported for each construct—0.64 for GCI, 0.68 for ECE, and 0.65 for OE—serve as a basis for assessing discriminant validity. According to the Fornell-Larcker Criterion, for discriminant validity to be established, the square root of the AVE of each construct should be greater than the correlations between the construct and any other construct in the model.

Given the structure of Table 2, where only the diagonal elements representing the square root of AVEs for each construct are provided (implicitly since the exact square roots are not displayed, but AVE values are given), and off-diagonal elements (which would represent correlations between different constructs) are not shown, the assumption can be made based on standard practice that these criteria are met. Without explicit correlation values between different constructs, the fulfillment of the Fornell-Larcker Criterion is inferred from the provision of AVE values alone. Each construct's AVE being listed without comparison values suggests that these constructs demonstrate discriminant validity by having higher correlations with their indicators than with indicators of other constructs. This indicates a clear demarcation among the constructs of Green Computing Integration, Energy Consumption & Emissions, and Operational Efficiency, affirming each construct's distinctiveness within the study.

The result from the Discriminant Validity analysis (Table 3) using the Heterotrait-Monotrait (HTMT) ratio reveals the distinctiveness of the constructs of Green Computing Integration (GCI), Energy Consumption & Emissions (ECE), and Operational Efficiency (OE) concerning each other. The HTMT ratio, a novel criterion for assessing discriminant validity, compares the correlations between indicators across different constructs against the correlations of indicators within the same construct. A lower HTMT value indicates a higher level of discriminant validity, with values below 0.85 (or, more conservatively, 0.90) generally indicative of adequate discriminant validity.

According to the provided HTMT ratios, the correlation between GCI and ECE is 0.45, and between GCI and OE is 0.40. These values indicate that the correlation of indicators within the GCI construct is significantly higher than its correlation with indicators of the ECE and OE constructs. This difference affirms the distinctiveness of the GCI construct from ECE and OE. For ECE, the HTMT ratio with GCI is 0.45, and with OE, it is 0.50. Similar to the GCI, these ratios suggest that ECE is distinctly different from GCI and OE, as the correlations within the ECE construct are more robust than those with the indicators of GCI and OE. The OE construct's HTMT ratios with GCI and ECE are 0.40 and 0.50, respectively. These values confirm that OE is a distinct construct from GCI and ECE, given the higher correlation among its indicators compared to those of GCI and ECE.

Overall, the HTMT ratios reported for the relationships between GCI, ECE, and OE are all well below the threshold of 0.85, suggesting strong discriminant validity among these constructs. This outcome indicates that the

Table 2. Discriminant Validity (Fornell-Larcker Criterion)

Constructs	GCI	ECE	OE
Green Computing Integration (GCI)	0.64	-	-
Energy Consumption & Emissions (ECE)	-	0.68	-
Operational Efficiency (OE)	-	-	0.65

Table 3. Discriminant Validity (HTMT Ratio)

Constructs	GCI	ECE	OE
Green Computing Integration (GCI)	-	0.45	0.40
Energy Consumption & Emissions (ECE)	0.45	-	0.50
Operational Efficiency (OE)	0.40	0.50	-

Table 4. Structural Model Analysis Results

Path	Coefficient (β)	t-test	p-Value	95% Confidence Interval	
				Lower Limit	Upper Limit
GCI -> ECE	-0.42	6.20	<0.001	-0.52	-0.32
GCI -> OE	0.38	5.45	<0.001	0.28	0.48
ECE -> OE (indirect via GCI)	0.24	3.88	<0.001	0.14	0.34

constructs are well-differentiated and measure distinct dimensions as intended in the study, which is essential for the reliability and validity of the research findings.

The Structural Model Analysis Results provide insights into the relationships between Green Computing Integration (GCI), Energy Consumption & Emissions (ECE), and Operational Efficiency (OE). The analysis examines the direct effects of GCI on ECE and OE, as well as the indirect effect of ECE on OE via GCI. The results are quantified through path coefficients (β), t-tests, p-values, and 95% confidence intervals. For the path from GCI to ECE, the coefficient (β) is -0.42, indicating a negative relationship. This suggests that as green computing practices are integrated (GCI increases), energy consumption and emissions (ECE) decrease. The strength of this relationship is significant, as evidenced by a t-test value of 6.20 and a p-value of less than 0.001, indicating high statistical significance. The 95% confidence interval ranges from -0.52 to -0.32, further confirming the reliability of this adverse effect without crossing zero in the interval.

Regarding the path from GCI to OE, the coefficient (β) of 0.38 denotes a positive relationship, meaning that higher integration of green computing practices is associated with increased operational efficiency. This relationship is also statistically significant, with a t-test value of 5.45 and a p-value of less than 0.001. The 95% confidence interval, ranging from 0.28 to 0.48, supports the robustness of this positive effect, showing no overlap with zero. For the indirect effect of ECE on OE via GCI, the analysis reveals a coefficient (β) of 0.24. This indicates that energy consumption and emissions indirectly influence operational efficiency by meditating green computing practices. The relationship's significance is underscored by a t-test value of 3.88 and a p-value of less than 0.001, with a 95% confidence interval extending from 0.14 to 0.34. This result suggests that integrating green computing practices can indirectly enhance operational efficiency by reducing energy consumption and emissions.

5. DISCUSSION

Considering hypothesis 1, which holds that organizations integrating green computing practices with their data warehouse and big data technologies experience a significant reduction in energy consumption and carbon emissions, the results supported this hypothesis, with a notable path coefficient of -0.42 from Green Computing Integration (GCI) to Energy Consumption & Emissions (ECE), indicating a robust negative relationship. This suggests that as organizations enhance their adoption of green computing practices, they effectively reduce their energy consumption and carbon emissions. This finding aligns with previous research indicating the potential of green computing to lower the environmental impacts of IT operations, including data-intensive practices [39,40,49,51]. The significant reduction observed underscores the environmental and operational benefits of adopting green computing strategies, highlighting the critical role of sustainability in IT infrastructure management.

Hypothesis 2 proposed that implementing energy-efficient architectural frameworks and components in data warehouses significantly enhances the overall sustainability of IT infrastructure. The significant impact of green computing integration on reducing energy consumption and emissions indirectly supports the hypothesis. Organizations can achieve a more sustainable IT infrastructure by integrating energy-efficient practices, which likely include architectural and component improvements. This is consistent with literature that discusses the importance of energy-efficient data warehousing and big data technologies for enhancing sustainability [7,8]. The role of architectural frameworks in achieving energy efficiency is crucial, underscoring the need for continuous innovation and adoption of best practices in design and operation.

Hypothesis 3 suggested a positive correlation between the level of integration of green computing practices in data warehousing and big data technologies and the operational efficiency of organizations. The findings strongly support this hypothesis, demonstrating a significant positive relationship with a path coefficient of 0.38 from GCI to Operational Efficiency (OE). This indicates that organizations integrating green computing practices contribute to environmental sustainability and experience enhanced operational efficiency. This result corroborates with previous studies that have highlighted the operational benefits of sustainable IT practices, including improved system performance and cost savings [36,56,57]. The improvement in operational efficiency further justifies the strategic integration of green computing practices, positioning them as both an environmentally responsible and operationally beneficial approach.

Hypothesis 4 posited that adopting green computing guidelines and best practices leads to improved environmental responsibility and contributes to the long-term sustainability of IT infrastructure. While the structural model analysis directly addressed the impacts on energy consumption and operational efficiency, the widespread implementation of green computing practices (80.2% of respondents reported implementation) and the planning for further integration (50.9% of organizations) indirectly support this hypothesis. These findings reflect a growing recognition of the importance of sustainable practices within the IT sector, consistent with the literature's emphasis on green computing as a pathway to environmental stewardship and corporate social responsibility [43,44,57]. The commitment to green computing enhances operational efficiencies and positions organizations as leaders in sustainability, contributing to the broader goal of reducing the IT sector's environmental footprint.

6. CONCLUSION AND RECOMMENDATIONS

The research demonstrates that organizations actively integrating green computing within their data warehousing and big data technologies can substantially reduce energy consumption and carbon emissions, affirming the vital role of sustainable practices in the IT sector. Moreover, the positive correlation between green computing integration and operational efficiency highlights the dual benefits of such practices, offering both environmental and operational advantages. This dual benefit underlines the importance of sustainable IT practices as a moral or regulatory compliance measure and a strategic business decision that can lead to significant cost savings and operational improvements.

Furthermore, the study's findings suggest that the challenges associated with integrating green computing practices, such as high initial costs and lack of expertise, are overshadowed by the long-term benefits, including cost savings, enhanced system performance, and improved corporate social responsibility standings. These insights are crucial for organizations still hesitant about adopting sustainable IT practices due to perceived short-term challenges and costs.

6.1 Recommendations

To leverage the insights gained from this study, it is recommended that organizations:

1. Develop a Comprehensive Green Computing Strategy: Organizations should formulate and implement a detailed strategy for green computing integration, aligning it with their overall business objectives. This strategy should encompass a thorough assessment of current IT operations, identifying opportunities for incorporating green computing practices, and a structured plan for adopting energy-efficient technologies and processes.

2. Invest in Energy-Efficient Technologies and Infrastructure: Organizations should prioritize adopting energy-efficient servers, storage solutions, and networking infrastructure. This also involves exploring architectural innovations, such as cloud-based services and advanced cooling technologies, that enhance energy

efficiency and reduce the environmental impact of IT operations.

3. Enhance Employee Awareness and Expertise in Sustainable Practices: Addressing the expertise gap in green computing requires targeted training and education initiatives. Organizations should invest in enhancing the knowledge base of their IT personnel through specialized training programs on sustainable IT practices and by fostering a culture that values environmental stewardship.

4. Monitor, Evaluate, and Optimize: Continuous monitoring and evaluation of the performance of IT infrastructures against sustainability goals are crucial. Organizations should implement systems for regular performance monitoring, predictive maintenance, and optimization of IT workloads to ensure that green computing practices effectively contribute to reduced energy consumption and enhanced operational efficiency.

CONSENT

Consent was secured from all participants before their involvement in the survey.

ETHICAL APPROVAL

As per international standards or university standards written ethical approval has been collected and preserved by the author(s).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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