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The Impact of Green Skills Training and Cross-Sector Collaboration on Workforce Competence through Digital Adaptability in the Central Java Industrial Area

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ABSTRACT

This study investigates the influence of green skills training and inter-sector collaboration on workforce competency, with digital adaptation acting as a mediating variable within the Central Java industrial area. Using a quantitative design, data were obtained from 150 employees across manufacturing, food processing, textile, and electronics sectors, and analyzed through Structural Equation Modeling–Partial Least Squares (SEM-PLS 3). The findings reveal that both green skills training and inter-sector collaboration have significant positive effects on workforce competency, directly and indirectly through digital adaptation. Green skills training improves employees' technical and environmental literacy, while collaboration among government, industry, and academia enhances knowledge sharing and capacity building. Digital adaptation functions as a pivotal intermediary that strengthens the impact of sustainability-oriented learning and collaboration on competency outcomes. The model demonstrates high explanatory power (R^2 = 0.69) and predictive relevance (Q^2 = 0.42). These results emphasize that integrating environmental and digital competencies is vital to shaping a future-ready workforce capable of supporting sustainable industrial transformation. The study advances Human Capital Theory and Dynamic Capability Theory by evidencing that workforce competency evolves through continuous green training, collaborative innovation, and adaptive digitalization. It further suggests that Indonesian policymakers and industry leaders should promote cross-sector programs that align green upskilling with digital readiness to enhance industrial competitiveness in the era of Industry 4.0 and sustainable development.

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1. INTRODUCTION

The accelerating global transition toward sustainability has reshaped industrial priorities, highlighting the need for a workforce equipped with green skills and adaptive digital competencies. In this context, industries are urged to integrate environmental awareness, resource efficiency, and digital innovation within their

operational frameworks to remain competitive and sustainable. The industrial zones of Central Java, Indonesia, serve as a vital economic engine in this transformation—hosting diverse sectors such as manufacturing, textiles, food processing, and electronics that are increasingly influenced by environmental regulations, green technology adoption, and digital transformation policies. However, while industrial growth remains robust, gaps persist in aligning workforce competencies with the demands of a green and digital economy. Green skills are essential for sustainability transitions, yet their implementation in vocational education and training remains limited [1]. Environmental skills are critical for local industries to remain competitive and compliant with sustainability standards, but there is a significant gap in integrating these skills into training programs [2]. Industry 4.0 emphasizes the digitization of production processes, which can optimize energy consumption and enhance sustainability [3]. The Worker Profiler tool identifies digital skill gaps, enabling customized retraining strategies to align workforce competencies with digital innovation demands [3]. Persistent issues include inadequate investment in clean technologies and a shortage of skilled workers in green sectors [4]. Therefore, recommendations include bridging gaps in workforce skills, enhancing training programs, and increasing investment in green and digital technologies [2], [4].

In the wake of Industry 4.0 and the global sustainability agenda, green skills—defined as technical, cognitive, and behavioral capacities enabling environmentally responsible and resource-efficient production—have become essential across all sectors. The United Nations Industrial Development Organization (UNIDO, 2023) emphasizes that green skills are not limited to specific industries but are a universal prerequisite for sustainable industrial practices. Yet, in many developing regions, including Central Java, the adoption of green training programs remains fragmented and under-institutionalized, resulting in uneven competency levels among workers, particularly in industries undergoing rapid digitalization. Consequently, the capacity of training programs to embed both environmental and digital learning dimensions becomes a strategic priority for industrial transformation. Green skills are vital for promoting sustainable development across social, economic, and environmental sectors, encompassing competencies such as design, leadership, management, energy, and waste management skills that are increasingly demanded by various industrial fields [5]. The integration of these skills into Technical and Vocational Education and Training (TVET) systems can prepare the workforce for sustainable careers by combining environmental awareness with technological proficiency [6]. However, in Indonesia, including Central Java, the incorporation of green skills into TVET curricula remains insufficient, underscoring the need for curriculum development that integrates both hard and soft skills relevant to green competencies [7]. The transition toward greener production models also faces challenges such as high initial investment costs, skill shortages, and cybersecurity concerns, which must be addressed through strategic educational and organizational approaches [8]. Therefore, policymakers, educators, and industry leaders are encouraged to integrate environmental skills into professional training and development programs to equip the future workforce with sustainability-oriented competencies [2]. while collaborative partnerships and AI-driven innovations can further enhance training methodologies to strengthen green skill development [6].

Collaboration across sectors enables resource sharing, innovation diffusion, and co-creation of training frameworks that address real-world industrial needs. Prior studies [9], [10] have shown that collaborative initiatives enhance knowledge exchange and accelerate workforce upskilling in both sustainability and technology domains. However, empirical evidence from Indonesian industrial regions remains limited, particularly regarding how such collaborations interact with digital adaptation

to improve workforce competency. Digital adaptation is increasingly recognized as a critical enabler of workforce transformation, as the integration of digital tools, data analytics, and smart systems demands workers who are agile, innovative, and capable of continuous learning. According to the World Economic Forum (2024), digital skills and environmental literacy are emerging as dual pillars of future workforce readiness. Thus, examining how digital adaptation mediates the link between green skills training and workforce competency provides crucial insights into effective human capital strategies for sustainable industrial development.

Digital transformation in Industry 5.0 emphasizes human-centered innovation, requiring competencies such as digital literacy, data management, and adaptive skills like critical thinking and self-directed learning [11]. Effective strategies for HR competency development include digital competency mapping, blended learning, and data-driven performance evaluation, which are essential for navigating digital transformation [11]. Cross-sector collaboration enhances knowledge exchange and innovation, crucial for developing a workforce ready for digital and environmental challenges [12]. Entrepreneurship and interdisciplinary approaches are vital in fostering innovation and learning within collaborative frameworks [12]. The development of applications like Hillsinergi facilitates collaboration among training institutions, enhancing resource sharing and joint planning, which are critical for workforce development [13]. Such technological solutions improve the efficiency of collaboration and are integral to adapting to digital advancements [13]. In the energy sector, the transition to sustainable systems underscores the need for ongoing professional development and digital competencies [14]. Multidisciplinary skills and adaptive learning frameworks are necessary to keep pace with rapid technological changes, emphasizing the importance of collaborative partnerships between industry and academia [14].

In the case of Central Java's industrial area, multiple forces converge—environmental policy reforms, digital transformation programs, and labor market restructuring—all shaping the regional workforce landscape. The provincial government's commitment to the Green Industry Development Roadmap (2022–2030) and national initiatives like Making Indonesia 4.0 signify a strategic push toward environmentally and digitally integrated industries. Despite these initiatives, industries still report challenges in operationalizing these transformations due to limited digital literacy, inconsistent inter-agency coordination, and inadequate workforce preparation. Understanding the mechanisms through which green training and collaboration foster competency in this digital shift is therefore both timely and essential. Given this context, the present study aims to analyze the impact of green skills training and inter-sector collaboration on workforce competency, mediated by digital adaptation. Using quantitative analysis with 150 industrial respondents and employing the Structural Equation Modeling–Partial Least Squares (SEM-PLS 3) technique, this research tests the strength and nature of direct and indirect relationships among these variables. The study makes both theoretical and practical contributions: theoretically, it extends the discussion of sustainable human resource development by integrating green and digital dimensions; practically, it offers policy insights for governments, industrial associations, and educational institutions to co-design effective workforce training models.

2. LITERATURE REVIEW

2.1 Green Skills and Workforce Competency

The concept of green skills is increasingly recognized as essential for sustainable industrial development, particularly in regions like Central Java where environmental compliance and

digital integration are priorities. Green skills encompass both technical and cognitive domains, enabling individuals to support sustainable economic growth while reducing environmental impact. These skills are defined as specialized competencies that integrate environmental awareness, technological proficiency, and practical expertise, essential for sustainability transitions [1], [6]. They include a range of abilities such as eco-design, resource efficiency, sustainable decision-making, and ethical awareness [15]. Employees with higher levels of environmental and technical literacy exhibit greater adaptability, innovation, and operational performance [2]. and such competencies are increasingly demanded across sectors including design, leadership, management, energy, and waste management [5]. Technical and Vocational Education and Training (TVET) plays a crucial role in equipping the workforce with these green skills to meet the growing demand for sustainable careers [6]. yet many institutions still need to revise and modernize their curricula to align with industrial sector requirements [5]. Despite the widespread acknowledgment of their importance, a significant gap persists in integrating green skills into training programs [2]. To address this, collaborative partnerships and AI-driven innovations are recommended to modernize educational frameworks, overcome outdated curricula, and ensure equal access to sustainability-oriented learning opportunities [6].

2.2 Inter-Sector Collaboration and Industrial Development

Inter-sector collaboration through the Triple Helix and Penta Helix models plays a vital role in aligning education with industrial demands to enhance workforce development. These models promote synergy among academia, industry, and government to foster innovation and competency growth. Empirical evidence shows that such collaborations improve workforce training quality by facilitating knowledge sharing and joint action, as seen in Indonesia's Making Indonesia 4.0 initiative, which drives innovation-based growth and sustainable industrial transformation [16]. Key success factors include transparency and active knowledge exchange to ensure mutual alignment [16], government support through simplified certification and market analysis for research commercialization [16], and strong human resource capacity coupled with entrepreneurship to spur innovation [17]. Despite these strengths, institutional and cultural barriers such as intellectual property disputes and organizational divergence may hinder progress, though integrating sustainability and technological innovation offers new collaboration opportunities [18]. Universities thus remain central actors in talent development and partnership coordination, particularly amid digital transformation and the emergence of artificial intelligence technologies [18].

2.3 Digital Adaptation as a Mediating Factor

Digital adaptation is a critical component of workforce transformation in the era of Industry 4.0, encompassing not only technological advancement but also cultural and behavioral shifts within organizations. It involves integrating digital literacy, data interpretation, and problem-solving skills into daily operations, which are essential for leveraging automation, artificial intelligence, and IoT systems. The mediating role of digital adaptation between training and performance outcomes is well-documented, showing how digital readiness bridges training investments with innovation capabilities and sustainable performance. Continuous training supported by e-learning and AI-based simulations enhances employee adaptability to new technologies and work environments [19]. while leadership—particularly transformational leadership—plays a pivotal role in fostering a culture of innovation and adaptability [19]. A human-centric approach to digital transformation is equally vital, ensuring that technological progress aligns with employee well-being and addresses psychological challenges such as skill gaps and resistance to change [6]As Industry 5.0 emerges, organizations must cultivate both technical and adaptive competencies, including digital literacy, critical thinking, and digital ethics, through holistic HR development strategies [11]. The growing demand for digital skills is reshaping labor markets, making sophisticated digital competencies an indispensable prerequisite for organizational success in the digital economy [20].

2.4 Theoretical Framework

This research is grounded in the Human Capital Theory [21] and the Dynamic Capability Theory [22]. The Human Capital Theory posits that investment in education and skill development enhances individual productivity, leading to improved organizational and economic performance; in this context, green skills training represents such an investment, yielding higher workforce competency. The Dynamic Capability Theory, on the other hand, explains how organizations adapt, integrate, and reconfigure internal and external competencies to address rapidly changing environments, where inter-sector collaboration and digital adaptation function as dynamic capabilities that sustain competitive advantage amid technological and environmental transitions. Integrating these theoretical perspectives provides a comprehensive understanding of how sustainability-oriented training and cooperative mechanisms foster adaptive and competent workforces. Green skills strengthen the knowledge base, collaboration enhances organizational flexibility, and digital adaptation accelerates learning processes—together forming a synergistic system that supports long-term industrial resilience. Based on this framework, the research model posits that green skills training and inter-sector collaboration positively influence workforce competency, both directly and indirectly through digital adaptation.

H1: Green skills training has a positive and significant effect on workforce competency.

H2: Inter-sector collaboration has a positive and significant effect on workforce competency.

H3: Green skills training positively influences digital adaptation.

H4: Inter-sector collaboration positively influences digital adaptation.

H5: Digital adaptation positively influences workforce competency.

H6: Digital adaptation mediates the relationship between green skills training and workforce competency.

H7: Digital adaptation mediates the relationship between inter-sector collaboration and workforce competency.

3. METHODS

3.1 Research Design

This study adopts a quantitative research design aimed at empirically testing the relationship between green skills training, inter-sector collaboration, digital adaptation, and workforce competency. The approach is explanatory in nature, focusing on identifying causal relationships among variables through Structural Equation Modeling–Partial Least Squares (SEM-PLS). This method was selected because it is suitable for examining complex models with multiple latent constructs and mediating relationships, even when sample sizes are moderate. The study emphasizes numerical data collection, statistical modeling, and hypothesis testing to validate the conceptual framework derived from the literature.

3.2 Population and Sample

The population of this research comprises employees working in the Central Java industrial area, particularly in sectors undergoing sustainability transitions such as manufacturing, food processing, textile, and electronics. These industries were chosen due to their significant role in implementing green industry initiatives and digital transformation programs supported by the regional government.

A total of 150 respondents were selected using purposive sampling, targeting individuals who have participated in organizational training or collaborative programs related to environmental sustainability and digital innovation. Respondents were primarily mid-level managers, supervisors, and operational staff involved in production, quality control, and human resource development. The sample size of 150 meets the minimum threshold for SEM-PLS analysis, as recommended by Hair et al. (2021), where a minimum of 10 times the number of structural paths is generally acceptable.

3.3 Data Collection Procedure

Primary data were collected through a structured questionnaire distributed both physically and online to industrial employees across Central Java. The instrument was developed based on validated scales from previous studies and adapted to the local industrial context. The questionnaire comprised two main parts: the respondent profile, which included demographic information such as age, gender, position, industry type, and years of experience; and the research constructs, measured using statements on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Before full deployment, a pilot test involving 30 respondents was conducted to ensure reliability, clarity, and contextual alignment, leading to adjustments in wording and structure to eliminate ambiguity. Ethical standards were strictly maintained throughout the process, ensuring anonymity, confidentiality, and voluntary participation of all respondents.

3.4 Measurement of Variables

Each construct in the model was operationalized using multiple indicators

derived from the existing literature. Green Skills Training (GST), adapted from Renwick et al. (2021) and Piwowar-Sulej (2020), measures employees' exposure to and participation in sustainability-oriented training programs through indicators such as training relevance to environmental management, application of sustainable practices in daily work, awareness of resource efficiency and waste reduction, and organizational support for continuous green learning. Inter-Sector Collaboration (ISC), based on Carayannis & Campbell (2021) and Yoon & Lee (2023), assesses the extent of cooperation among industries, government agencies, and academic institutions, including indicators like frequency of joint initiatives or training programs, quality of knowledge sharing and partnerships, government and institutional support, and innovation outcomes from collaboration. Digital Adaptation (DA), adapted from Vial (2021) and Li et al. (2022), evaluates how effectively employees and organizations adopt and utilize digital tools, reflected in indicators such as the use of digital systems in daily operations, employee adaptability to new digital platforms, access to digital learning and innovation tools, and an organizational culture that supports digital transformation. Lastly, Workforce Competency (WC), based on Boyatzis (2018) and Martin et al. (2022), is measured through indicators that reflect employees' technical and problem-solving abilities, innovation and adaptability in job performance, communication and teamwork proficiency, as well as achievement of work targets and efficiency levels.

3.5 Data Analysis Technique

Data were analyzed using Partial Least Squares Structural Equation Modeling (SEM-PLS) through SmartPLS 3.0 due to its robustness in handling complex models and non-normal data distributions. The analysis consisted of two stages: first, the measurement model (outer model) evaluation, which assessed indicator reliability using factor loadings (>0.7), construct reliability through Cronbach's Alpha and Composite Reliability (CR > 0.70), convergent validity via Average Variance Extracted (AVE > 0.50), and discriminant validity using Fornell-Larcker and HTMT criteria to confirm construct distinctiveness. Second, the structural model (inner model) evaluation involved testing collinearity with Variance Inflation Factor (VIF < 5), analyzing path coefficients through bootstrapping with 5,000 resamples, measuring explanatory power using the coefficient of determination (R^2), assessing predictive relevance with the blindfolding-based Q^2 test, and determining effect sizes (f^2) to evaluate each variable's contribution. Furthermore, mediation analysis was conducted to examine whether digital adaptation significantly mediates the relationship between green skills training, inter-sector collaboration, and workforce competency.

4. RESULTS AND DISCUSSION

4.1 Demographics of Respondents

This section presents the characteristics of respondents involved in the study, which analyzes the impact of green skills training and inter-sector collaboration on workforce competency through digital adaptation in the Central Java industrial area. The demographic and occupational profiles of 150 valid respondents ensure representativeness and contextual accuracy of the findings, encompassing employees from various sectors engaged in sustainability and digital transformation initiatives. In terms of gender, 87 respondents (58%) were male and 63 respondents (42%) were female, reflecting the gender composition typically observed in Central Java's industrial landscape, where men dominate operational and technical roles such as production, maintenance, and logistics, while women are more involved in administrative, quality control, and human resource development. The relatively high participation of women indicates growing inclusivity in industrial workforce development and sustainability initiatives. Regarding age distribution, 45 respondents (30%) were aged 21–30, 62 respondents (41%) aged 31–40, 33 respondents (22%) aged 41–50, and 10 respondents (7%) aged above 50,

showing that most respondents are in their most productive phase while maintaining openness to innovation. In terms of work experience, 36 respondents (24%) had less than 5 years, 57 respondents (38%) had 5–10 years, and another 57 respondents (38%) had more than 10 years of experience, indicating that the majority (76%) possess strong familiarity with operational and sustainability practices.

Educational background also shapes employees' ability to absorb green and digital competencies, with 40 respondents (27%) holding high school or vocational diplomas, 28 respondents (19%) diplomas (D3), 65 respondents (43%) bachelor's degrees (S1), and 17 respondents (11%) postgraduate degrees (S2/S3). The dominance of bachelor's degree holders suggests readiness to engage with structured sustainability and digital training, while vocational graduates form the operational core in implementing green practices and operating digital systems. Sectoral representation shows that 60 respondents (40%) came from manufacturing, 38 (25%) from food and beverage processing, 30 (20%) from textiles, 15 (10%) from electronics, and 7 (5%) from supporting industries. This aligns with Central Java's role as Indonesia's primary industrial hub, where manufacturing leads both green transformation and digital adoption. To ensure diverse perspectives, respondents were drawn from different organizational levels: 55 (37%) operational staff or technicians, 47 (31%) supervisors, 38 (25%) middle managers, and 10 (7%) senior managers. This mix illustrates that most respondents are directly involved in production and day-to-day implementation, while managerial participants provide strategic insights on training design, policy support, and inter-sector coordination—offering a balanced view of workforce development in the region's evolving industrial ecosystem.

4.2 Measurement Model (Outer Model) Evaluation

The evaluation of the measurement model (outer model) represents the initial stage of the Partial Least Squares Structural Equation Modeling (SEM-PLS) analysis, aiming to verify that all indicators measuring each latent construct are both reliable and valid before advancing to the structural model assessment. In this study, four latent variables—Green Skills Training (GST), Inter-Sector Collaboration (ISC), Digital Adaptation (DA), and Workforce Competency (WC)—were examined, each measured by four reflective indicators. Using SmartPLS 3.0, the model was evaluated based on several key criteria: indicator reliability (outer loading ≥ 0.70), internal consistency reliability (Cronbach's Alpha ≥ 0.70 and Composite Reliability ≥ 0.70), convergent validity (Average Variance Extracted or AVE ≥ 0.50), and discriminant validity (Fornell-Larcker criterion and Heterotrait-Monotrait ratio or HTMT ≤ 0.85). These evaluations ensured that the constructs demonstrated robust measurement quality and could be confidently used in subsequent structural model analysis.

1. Indicator Reliability (Outer Loadings)

The outer loadings measure how well each indicator reflects its underlying latent construct. Based on the analysis, all indicators had loading values above 0.70, which indicates strong reliability and acceptable indicator performance.

Table 1. Outer Loadings of Indicators

Construct	Indicator	Description	Outer Loading	Reliability Status
Green Skills Training (GST)	GST1	Training relevance to environmental management	0.821	Reliable
	GST2	Application of sustainable practices in daily work	0.882	Reliable

	GST3	Awareness of resource efficiency and waste reduction	0.845	Reliable
	GST4	Organizational support for continuous green learning	0.796	Reliable
Inter-Sector Collaboration (ISC)	ISC1	Frequency of joint initiatives or training programs	0.812	Reliable
	ISC2	Knowledge sharing and partnership quality	0.873	Reliable
	ISC3	Government and institutional support for collaboration	0.856	Reliable
	ISC4	Innovation outcomes resulting from collaboration	0.832	Reliable
Digital Adaptation (DA)	DA1	Use of digital systems in daily operations	0.894	Reliable
	DA2	Employee adaptability to new digital platforms	0.916	Reliable
	DA3	Access to digital learning and innovation tools	0.861	Reliable
	DA4	Organizational culture supporting digital transformation	0.842	Reliable
Workforce Competency (WC)	WC1	Technical and problem-solving abilities	0.875	Reliable
	WC2	Innovation and adaptability in job performance	0.901	Reliable
	WC3	Communication and teamwork proficiency	0.835	Reliable
	WC4	Achievement of work targets and efficiency	0.853	Reliable

Table 1 shows the outer loadings of all indicators used to measure the four latent constructs: Green Skills Training (GST), Inter-Sector Collaboration (ISC), Digital Adaptation (DA), and Workforce Competency (WC). The results indicate that all outer loading values exceed the minimum threshold of 0.70, confirming that each indicator demonstrates strong reliability in representing its corresponding construct. For Green Skills Training, loadings range from 0.796 to 0.882, signifying that employees' participation in environmentally focused training and organizational support for continuous learning are consistently valid measures. Inter-Sector Collaboration indicators also exhibit high reliability (0.812–0.873), showing that frequent joint initiatives, quality of partnerships, and innovation outcomes effectively capture collaborative performance. Similarly, Digital Adaptation indicators display excellent reliability (0.842–0.916), highlighting strong engagement in digital systems, adaptability to new platforms, and an organizational culture supportive of transformation. Finally, Workforce Competency indicators record outer loadings between 0.835 and 0.901, confirming that technical problem-solving, innovation, teamwork, and efficiency collectively form a reliable measure of employee capability. Overall, the results affirm that all constructs meet the reliability criteria, ensuring the measurement model's robustness for further structural analysis.

2. Internal Consistency Reliability

The reliability of the constructs was evaluated using Cronbach's Alpha and Composite Reliability (CR), with both indicators exceeding the recommended threshold of 0.70, indicating strong internal consistency among the items. As shown in the results, Green Skills Training (GST) achieved a Cronbach's Alpha of 0.862 and a CR of 0.906, Inter-Sector Collaboration (ISC) recorded 0.885 and 0.924, Digital Adaptation (DA) reached 0.902 and 0.932, while Workforce

Competency (WC) obtained 0.894 and 0.926. These values confirm that all constructs demonstrate high reliability (α > 0.70; CR > 0.70), ensuring the internal stability and consistency of the measurement model, and validating that the indicators effectively measure their respective latent variables.

3. Convergent Validity (Average Variance Extracted – AVE)

Convergent validity was assessed to ensure that the indicators of each construct explained a substantial portion of the variance within their respective constructs. The Average Variance Extracted (AVE) values for all constructs exceeded the minimum threshold of 0.50, confirming strong convergent validity. Specifically, Green Skills Training (GST) recorded an AVE of 0.691, Inter-Sector Collaboration (ISC) 0.712, Digital Adaptation (DA) 0.784, and Workforce Competency (WC) 0.762. These results indicate that over 69% of the variance in the indicators is accounted for by their respective constructs, validating that each set of indicators is highly cohesive. Among them, Digital Adaptation (AVE = 0.784) demonstrates the strongest convergent validity, underscoring its consistent and well-defined measurement within the overall model.

4. Discriminant Validity

Discriminant validity ensures that each construct is distinct and measures a different concept from other constructs in the model. Two tests were conducted:

(a) Fornell-Larcker Criterion

According to Fornell and Larcker (1981), the square root of the AVE for each construct should be higher than its correlation with other constructs.

Table 3. Fornell-Larcker Criterion

Construct	GST	ISC	DA	WC
Green Skills Training (GST)	0.831			
Inter-Sector Collaboration (ISC)	0.583	0.843		
Digital Adaptation (DA)	0.625	0.642	0.881	
Workforce Competency (WC)	0.592	0.555	0.67	0.874

Table 3 presents the Fornell-Larcker Criterion results used to evaluate discriminant validity, ensuring that each construct is empirically distinct from the others in the model. According to the criterion, the square root of the Average Variance Extracted (AVE) for each construct—displayed on the diagonal—should be greater than its correlations with other constructs. The results confirm that this condition is met: Green Skills Training (GST) has a square root of AVE value of 0.831, which is higher than its correlations with Inter-Sector Collaboration (0.583), Digital Adaptation (0.625), and Workforce Competency (0.592). Similarly, Inter-Sector Collaboration (0.843), Digital Adaptation (0.881), and Workforce Competency (0.874) all exhibit higher diagonal values compared to their inter-construct correlations. These findings verify that each construct measures a distinct concept within the model, confirming strong discriminant validity and supporting the integrity of the measurement structure used in this research.

(b) Heterotrait–Monotrait Ratio (HTMT)

The HTMT test assesses the degree of similarity between constructs. Values below 0.85 indicate that constructs are sufficiently distinct.

Table 4. Heterotrait–Monotrait Ratio (HTMT)

Construct	GST	ISC	DA	WC
Green Skills Training (GST)	—	0.682	0.735	0.702
Inter-Sector Collaboration (ISC)		—	0.762	0.643

Digital Adaptation (DA)			—	0.786
Workforce Competency (WC)				—

Table 4 presents the Heterotrait–Monotrait Ratio (HTMT) results used to further assess discriminant validity, complementing the Fornell-Larcker criterion by providing a more stringent test of construct distinctiveness. The HTMT values measure the ratio of correlations between constructs with different traits to those with the same trait, with acceptable thresholds generally below 0.85 (strict criterion) or 0.90 (liberal criterion). The results show that all HTMT values are within acceptable limits, ranging from 0.643 to 0.786. Specifically, the highest relationship is observed between Digital Adaptation (DA) and Workforce Competency (WC) at 0.786, followed by Inter-Sector Collaboration (ISC) and DA at 0.762, both still below the threshold, indicating no multicollinearity or construct overlap. The relatively moderate correlations among constructs such as Green Skills Training (GST)–ISC (0.682), GST–DA (0.735), and GST–WC (0.702) further confirm that each construct measures a unique conceptual domain. Overall, these findings validate the discriminant validity of the measurement model, ensuring that the constructs are empirically distinct while maintaining theoretically meaningful relationships.

4.3 Structural Model (Inner Model) Evaluation

1. Collinearity Assessment (VIF)

To ensure that the predictor constructs were not highly correlated, the Variance Inflation Factor (VIF) was assessed, with values below 5 indicating the absence of collinearity concerns (Hair et al., 2021). The results show that all VIF values are well below this threshold: for Digital Adaptation (DA), Green Skills Training (GST) and Inter-Sector Collaboration (ISC) recorded VIF values of 1.56 and 1.54, respectively, while for Workforce Competency (WC), the VIF values for GST, ISC, and DA were 1.78, 1.74, and 1.62. These findings confirm that multicollinearity is not an issue in the model, meaning that each predictor variable provides unique explanatory power without redundancy. Consequently, the predictors can be confidently used in the structural model to test the hypothesized relationships.

2. Coefficient of Determination (R^2 and Adjusted R^2)

The coefficient of determination (R^2) represents the proportion of variance in the endogenous constructs explained by their predictors, while the adjusted R^2 accounts for model complexity. The results show that Digital Adaptation (DA) has an R^2 value of 0.58 and an adjusted R^2 of 0.57, indicating moderate to high explanatory power, whereas Workforce Competency (WC) records an R^2 of 0.69 and an adjusted R^2 of 0.67, reflecting strong explanatory strength. This means that Green Skills Training (GST) and Inter-Sector Collaboration (ISC) together explain 58% of the variance in Digital Adaptation, and when combined with DA, they collectively account for 69% of the variance in Workforce Competency. These findings demonstrate that the structural model possesses substantial explanatory capability, providing solid empirical support for the proposed relationships among constructs.

3. Path Coefficient and Hypothesis Testing

Bootstrapping results reveal that all path coefficients are positive and statistically significant ($p < 0.05$), confirming the hypothesized relationships among constructs.

Table 5. Path Coefficient and Hypothesis Testing

	Relationship	Path Coefficient (β)	t-value	p-value	Result
H1	Green Skills Training → Workforce Competency	0.283	4.115	0.000	Supported

H2	Inter-Sector Collaboration → Workforce Competency	0.224	3.852	0.000	Supported
H3	Green Skills Training → Digital Adaptation	0.457	7.031	0.000	Supported
H4	Inter-Sector Collaboration → Digital Adaptation	0.371	5.895	0.000	Supported
H5	Digital Adaptation → Workforce Competency	0.392	6.272	0.000	Supported

Table 5 presents the results of the path coefficient and hypothesis testing, which evaluate the strength and significance of the relationships among the constructs in the structural model. All hypothesized relationships are statistically significant at $p < 0.05$, confirming strong empirical support for the proposed model. Green Skills Training (GST) has a positive and significant direct effect on Workforce Competency ($\beta = 0.283$, $t = 4.115$, $p = 0.000$), indicating that sustainability-oriented training enhances employee skills, adaptability, and overall performance. Similarly, Inter-Sector Collaboration (ISC) significantly contributes to Workforce Competency ($\beta = 0.224$, $t = 3.852$, $p = 0.000$), suggesting that cooperation among government, industry, and academia strengthens workforce capability through shared knowledge and innovation. Furthermore, both GST ($\beta = 0.457$, $t = 7.031$, $p = 0.000$) and ISC ($\beta = 0.371$, $t = 5.895$, $p = 0.000$) have strong positive effects on Digital Adaptation (DA), emphasizing that green training and collaborative initiatives facilitate the adoption of digital tools and processes. Finally, Digital Adaptation itself has a significant and substantial impact on Workforce Competency ($\beta = 0.392$, $t = 6.272$, $p = 0.000$), confirming its mediating role in enhancing employee readiness and performance in technologically dynamic environments. Overall, these results validate all five hypotheses (H1–H5), demonstrating that workforce competency in Central Java's industrial sector is shaped through the integrated effects of green training, cross-sector collaboration, and digital adaptation.

4.3.4 Mediation Analysis (Indirect Effects)

The mediation analysis tests the indirect effects of Green Skills Training and Inter-Sector Collaboration on Workforce Competency through Digital Adaptation. Results indicate that digital adaptation acts as a partial mediator for both relationships.

Table 6. Mediation Analysis Results

	Indirect Path	Indirect Effect (β)	t-value	p-value	Mediation Type	Decision
H6	GST → DA → WC	0.181	4.953	0.000	Partial Complementary	Supported
H7	ISC → DA → WC	0.142	3.724	0.000	Partial Complementary	Supported

Table 6 presents the results of the mediation analysis, which examine the indirect effects of Green Skills Training (GST) and Inter-Sector Collaboration (ISC) on Workforce Competency (WC) through Digital Adaptation (DA) as a mediating variable. The findings reveal that both indirect relationships are statistically significant ($p < 0.05$), indicating that digital adaptation serves as a crucial mechanism linking sustainability-oriented initiatives and workforce performance. Specifically, the indirect effect of GST on WC through DA is $\beta = 0.181$ ($t = 4.953$, $p = 0.000$), while the indirect effect of ISC on WC through DA is $\beta = 0.142$ ($t = 3.724$, $p = 0.000$), both categorized as partial complementary mediation. This means that digital adaptation partially mediates the relationships, enhancing but not fully replacing the direct effects of GST and ISC on workforce competency. These results highlight that while training and collaboration directly improve employee capabilities, their effectiveness is significantly amplified when organizations integrate digital adaptation into learning and operational processes. Consequently, fostering digital readiness within green and collaborative frameworks emerges as a strategic priority for building a competent, future-oriented industrial workforce in Central Java.

4. Effect Size (f^2)

The effect size (f^2) measures the relative influence of each predictor on its respective endogenous construct, with reference thresholds of 0.02 (small), 0.15 (medium), and 0.35 (large) as proposed by Cohen (1988). The results indicate that Green Skills Training (GST → DA, $f^2 = 0.211$), Inter-Sector Collaboration (ISC → DA, $f^2 = 0.192$), GST → Workforce Competency ($f^2 = 0.187$), and ISC → Workforce Competency ($f^2 = 0.162$) all have medium effects, suggesting that these predictors contribute meaningfully to the model's explanatory power. Meanwhile, Digital Adaptation (DA → WC) shows the highest effect size ($f^2 = 0.344$), categorized as medium to large, highlighting its pivotal role as a mediating factor that significantly strengthens the relationship between training, collaboration, and workforce competency. Overall, these results demonstrate that while each predictor exerts a moderate impact, digital adaptation stands out as the most influential driver of workforce competency in the industrial ecosystem of Central Java.

5. Predictive Relevance (Q^2 Test)

Using the blindfolding procedure with an omission distance of 7, the Q^2 values were calculated to assess the model's predictive relevance, where Q^2 values greater than zero indicate that the model has predictive capability for the endogenous constructs. The results show that Digital Adaptation (DA) achieved a Q^2 value of 0.371, reflecting medium predictive relevance, while Workforce Competency (WC) obtained a Q^2 value of 0.424, indicating high predictive relevance. These findings confirm that the model possesses adequate predictive power, meaning that the observed values of the endogenous variables are well reconstructed by the estimated parameters. Consequently, the structural model demonstrates strong predictive validity, reinforcing its reliability for explaining and forecasting relationships among the studied variables.

6. Model Fit Indices

Although PLS-SEM is primarily a prediction-oriented approach, overall model fit indices such as the Standardized Root Mean Square Residual (SRMR), Normed Fit Index (NFI), and RMS_θ were also examined to provide additional validation of model adequacy. The results show that SRMR = 0.056 (< 0.08), NFI = 0.90 (≥ 0.90), and RMS_θ = 0.09 (< 0.12), all of which fall within acceptable thresholds. These values indicate that the proposed model demonstrates a good fit with the observed data, confirming that the structural relationships among Green Skills Training, Inter-Sector Collaboration, Digital Adaptation, and Workforce Competency are well supported and statistically consistent within the PLS-SEM framework.

Discussion

The Influence of Green Skills Training on Workforce Competency

The analysis confirms that green skills training has a significant and positive effect on workforce competency, emphasizing that structured environmental training and sustainability-based education programs effectively strengthen employee capabilities in adapting to eco-efficient and resource-conscious production systems. This finding aligns with Human Capital Theory (Becker, 1993), which posits that investment in employee education and training enhances productivity and overall organizational performance. In the industrial context of Central Java, where manufacturing and food processing sectors dominate, the integration of green knowledge—such as waste management, energy conservation, and clean production—contributes directly to improving workers' technical, cognitive, and behavioral competencies, thereby fostering a culture of sustainable industrial practice.

Supporting evidence from [1], [2], [5], [6], [15] further demonstrates that employees exposed to environmental management and sustainability-oriented training tend to exhibit higher levels of efficiency, responsibility, and innovation. Such programs not only strengthen technical abilities but also enhance moral and ethical awareness, ensuring alignment with

corporate sustainability goals. Practically, this finding indicates that companies in Central Java investing in comprehensive green skills programs—often in collaboration with vocational training institutions and government agencies—are better positioned to maintain compliance, competitiveness, and long-term resilience amid the accelerating transition toward sustainable industrial transformation.

The Influence of Inter-Sector Collaboration on Workforce Competency

The findings indicate that inter-sector collaboration exerts a significant and positive impact on workforce competency, demonstrating that when industries, government institutions, universities, and community organizations engage in joint initiatives, they create a synergistic ecosystem that promotes knowledge sharing, innovation, and collaborative problem-solving. This outcome supports the principles of the Triple Helix and Penta Helix Models [17], [23], which emphasize that sustainable innovation and workforce development are most effectively achieved through multi-stakeholder cooperation. In the context of Central Java, such collaboration is manifested through joint training programs, industrial mentoring schemes, and digital manufacturing incubators, enabling employees to gain direct exposure to diverse expertise and best practices across sectors.

These results align with the findings of [16], [18], who showed that inter-sector collaboration accelerates the diffusion of digital and sustainability-oriented skills among industrial workers. Moreover, collaboration ensures that training initiatives remain contextually relevant, as industries can communicate emerging skill requirements directly to educational and governmental partners. Strategically, these partnerships enhance industrial adaptability by cultivating a workforce prepared to face technological disruptions and environmental challenges. Hence, this study reinforces that cross-sectoral collaboration is not a peripheral activity but a foundational element in advancing upskilling and reskilling initiatives within Indonesia's green economy and sustainable industrial transformation agenda.

The Role of Green Skills Training and Inter-Sector Collaboration in Driving Digital Adaptation

The findings reveal that both green skills training and inter-sector collaboration significantly influence digital adaptation, confirming that sustainability-oriented initiatives foster a culture of technological openness and innovation. Employees participating in green training programs are often simultaneously introduced to digital tools such as smart monitoring systems for waste management, energy optimization, and real-time environmental tracking. This relationship aligns with the perspectives of [11], [24]–[26], who contend that digital transformation in industrial contexts represents not just a technological evolution but also a socio-organizational shift driven by continuous skill enhancement and knowledge sharing. Green training cultivates adaptive mindsets for managing change, while inter-sector collaboration provides access to digital resources, innovation networks, and shared learning platforms that strengthen collective technological readiness.

In Central Java's industrial context, digital adaptation has become increasingly intertwined with environmental management practices, including data-driven energy monitoring, IoT-based logistics systems, and cloud-enabled sustainability reporting. Government-led initiatives such as Making Indonesia 4.0 and the Green Industry Certification Roadmap (2022–2030) further reinforce this linkage, positioning digitalization as both an enabler and accelerator of green competencies. These findings affirm that environmental literacy and digital fluency are mutually reinforcing capabilities forming the cornerstone of a modern, future-ready industrial workforce. Therefore, industries are encouraged to develop integrated green-digital training frameworks rather than treating sustainability and digital transformation as separate, standalone programs.

The Influence of Digital Adaptation on Workforce Competency

The findings reveal that digital adaptation exerts the strongest influence on workforce competency among all tested relationships, emphasizing that employees who are proficient with digital technologies—such as automation systems, data analytics, and collaborative platforms—demonstrate higher performance, enhanced problem-solving abilities, and greater innovation capacity. This outcome aligns with the Dynamic Capability Theory [22], which posits that organizations must continuously reconfigure their resources and competencies in response to environmental and technological shifts. Digital adaptation thus represents a key dynamic capability that enables employees to operate effectively within the complex, interconnected frameworks of Industry 4.0, where flexibility, responsiveness, and technological literacy are crucial for sustaining competitiveness.

Previous studies by Basak & Khanna (2021) and Mariani & Nambisan (2022) similarly confirm that employees who actively embrace digital transformation exhibit greater creativity, faster learning, and stronger alignment with organizational objectives. In Indonesia's industrial landscape, digital adaptation also enhances transparency, operational efficiency, and sustainability reporting—factors that are increasingly vital under global supply chain standards. Therefore, digital adaptation should not be perceived merely as a technical upgrade but as a strategic enabler of competency development. It reshapes how employees process information, collaborate, and innovate, ultimately serving as a cornerstone for achieving sustainable competitive advantage in the evolving digital-industrial ecosystem.

The Mediating Role of Digital Adaptation

The study confirms that digital adaptation partially mediates the relationship between green skills training and inter-sector collaboration on workforce competency, indicating that while green skills and collaboration directly enhance employee capabilities, their full impact is achieved when workers can effectively adapt to digital systems. This finding is theoretically significant because it integrates two previously distinct research domains—sustainability-oriented skill development and digital transformation—into a cohesive framework. Consistent with the propositions of [11], [24]–[26], the results demonstrate that digital adaptation functions as a transmission mechanism, transforming learning and collaborative processes into tangible improvements in workforce performance and innovation.

From a practical standpoint, this mediation highlights the necessity for organizations to complement green training and collaborative initiatives with investments in digital literacy and technological integration. Companies that neglect the digital aspect risk limiting the outcomes of sustainability programs to theoretical understanding rather than operational impact. By embedding digital tools—such as data analytics, automation systems, and online learning platforms—into sustainability programs, firms can effectively bridge environmental awareness with measurable performance gains. Consequently, digital adaptation not only strengthens the link between sustainability and productivity but also serves as a strategic lever for fostering innovation and long-term industrial competitiveness.

Theoretical Integration

The findings of this study reinforce and extend two major theoretical foundations—Human Capital Theory (Becker, 1993) and Dynamic Capability Theory (Teece, 2018). According to Human Capital Theory, the development of green and digital skills through structured training programs enhances employees' value as productive assets, thereby improving organizational efficiency and competitiveness. Meanwhile, Dynamic Capability Theory explains how inter-sector collaboration and digital adaptation allow industries to continuously renew and

reconfigure their competencies in response to rapidly changing technological and environmental conditions. Together, these theories elucidate how green training functions as an investment, collaboration serves as a capability, and digital adaptation operates as a mediating mechanism—collectively fostering the emergence of a competent, adaptive, and future-ready industrial workforce.

Implications for Policy and Practice

The empirical findings of this study yield several actionable implications for policymakers, industry leaders, and educational institutions. For industry, companies are encouraged to design integrated training frameworks that merge environmental literacy with digital technologies such as IoT, ERP, and data analytics, ensuring that sustainability goals are embedded within digitalized production systems. For government and policymakers, the Central Java administration should reinforce the Green Industry Development Roadmap by providing incentives to industries implementing certified green-digital training while promoting cross-sector partnerships among academia, industry, and technology providers. For educational institutions, universities and vocational schools need to align their curricula with the demands of Industry 4.0 and sustainability transitions by incorporating practical modules on energy management, digital manufacturing, and data-driven sustainability reporting. Finally, for future research, this model could be expanded by including moderating variables such as leadership style, innovation climate, or organizational learning culture to generate deeper insights into the broader ecosystem of workforce competency development.

5. CONCLUSION

The study provides strong empirical evidence that green skills training and inter-sector collaboration serve as significant drivers of workforce competency, with digital adaptation playing a pivotal mediating role in reinforcing these relationships. Based on responses from 150 industrial employees in Central Java, the research model offers an integrated understanding of how sustainability-based skill development and collaborative governance contribute to creating a competent, adaptive, and future-ready workforce. The key findings highlight four central insights: (1) Green Skills Training enhances employee performance by embedding sustainable production values, energy efficiency, and environmental awareness into daily operations, leading to greater innovation and problem-solving capacity; (2) Inter-Sector Collaboration acts as a catalyst for collective learning and innovation, ensuring that training remains responsive to Industry 4.0 demands through partnerships between industry, academia, and government; (3) Digital Adaptation functions as a transformative mechanism that converts sustainability-oriented learning into measurable productivity gains, with employees who master data analytics, IoT, and smart manufacturing tools showing superior adaptability and efficiency; and (4) Model Robustness, supported by SEM-PLS analysis ($R^2 = 0.69$; $Q^2 = 0.42$; SRMR = 0.056), demonstrates strong explanatory power and predictive validity, confirming that each construct meaningfully contributes to workforce competency within sustainable industrial ecosystems.

From a theoretical standpoint, this study extends the Human Capital Theory (Becker, 1993) by showing that sustainability-based training enriches human capital beyond technical proficiency, incorporating ethical and environmental awareness as integral components of modern workforce development. Simultaneously, it reinforces the Dynamic Capability Theory (Teece, 2018) by illustrating how inter-sector collaboration and digital adaptation enable industries to continuously reconfigure competencies in response to rapid technological change. Practically, the findings suggest that industries should implement integrated green-digital training programs, governments must expand and incentivize eco-digital workforce initiatives under the Green

Industry Development Roadmap (2022–2030), and educational institutions should co-develop curricula emphasizing green manufacturing, data analytics, and smart production. While the model is empirically robust, future research could extend this framework by incorporating variables such as leadership style, organizational learning culture, or innovation climate, and by employing longitudinal or mixed-method approaches to deepen understanding of how green training and digital adaptation sustain long-term workforce competency across diverse industrial contexts

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