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Strategic Decarbonization in Mechatronics Supply Chains: Integrating Digital Technologies and Sustainable Operations

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Abstract

This study aimed to investigate the direct and indirect effects of digital technology adoption, sustainable operations, and supply chain integration on strategic decarbonization in mechatronics supply chains. This quantitative, applied, cross-sectional study was conducted among professionals working in mechatronics-related manufacturing, industrial automation, electronics, automotive components, robotics, control systems, and precision manufacturing companies in Tehran, Iran. Using purposive sampling, 348 questionnaires were distributed and 312 valid responses were retained for analysis. Participants included managers, engineers, supply chain specialists, operations personnel, sustainability experts, logistics professionals, procurement specialists, and information technology staff with at least two years of relevant experience. Data were collected using a structured questionnaire measuring digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization on a five-point Likert scale. Reliability and validity were assessed using Cronbach's alpha, composite reliability, average variance extracted, indicator loadings, and heterotrait-monotrait ratios. Partial least squares structural equation modeling was used to test direct and indirect relationships, with statistical significance evaluated through bootstrapping with 5,000 resamples. Digital technology adoption significantly predicted sustainable operations ($\beta = 0.61$, $p < 0.001$) and supply chain integration ($\beta = 0.31$, $p < 0.001$). Sustainable operations also significantly predicted supply chain integration ($\beta = 0.45$, $p < 0.001$). Strategic decarbonization was significantly predicted by digital technology adoption ($\beta = 0.18$, $p < 0.001$), sustainable operations ($\beta = 0.42$, $p < 0.001$), and supply chain integration ($\beta = 0.31$, $p < 0.001$). Significant indirect effects were identified through sustainable operations ($\beta = 0.26$, $p < 0.001$), supply chain integration ($\beta = 0.10$, $p < 0.001$), and the sequential pathway through both mediators ($\beta = 0.09$, $p < 0.001$). The model explained 68% of the variance in strategic decarbonization. Strategic decarbonization in mechatronics supply chains depends on the coordinated integration of digital capabilities, sustainable operational practices, and supply chain collaboration, with digital technologies contributing most effectively when translated into operational and interorganizational sustainability mechanisms.

Keywords: *Decarbonization, Mechatronics Supply Chains, Digital Technology Adoption, Sustainable Operations, Supply Chain Integration.*

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1. Introduction

Decarbonization has become one of the defining strategic challenges for contemporary industrial systems, as governments, firms, and supply chain networks are increasingly required to reconcile economic growth, technological development, and operational resilience with substantial reductions in greenhouse gas emissions. The transition toward low-carbon production is no longer confined to environmental compliance or isolated energy-efficiency measures; rather, it has evolved into a multidimensional process involving technological restructuring, supply chain redesign, changes in energy systems, new forms of industrial collaboration, and long-term organizational capability development. Early conceptualizations of decarbonization emphasized the need to act simultaneously on energy efficiency, low-carbon energy supply, infrastructure, and institutional transformation, demonstrating that achieving a zero-carbon future requires coordinated changes across economic and technological systems rather than incremental environmental improvements alone [1]. More recent research has reinforced this systemic perspective by showing that decarbonization pathways are shaped by interactions among economic development, governance quality, renewable energy transitions, investment patterns, technological readiness, and institutional capacity [2, 3]. Consequently, industrial decarbonization increasingly represents a strategic management issue in which organizations must determine how technological, operational, and interorganizational capabilities can be combined to reduce carbon intensity while preserving productivity, quality, flexibility, and competitiveness.

The complexity of this transition is particularly visible in industrial supply chains. A substantial share of organizational environmental impacts is generated not only within the focal firm's production boundaries but also through upstream sourcing, component manufacturing, transportation, energy use, logistics, supplier activities, and downstream distribution. Decarbonization strategies that focus exclusively on internal manufacturing operations may therefore overlook major sources of emissions embedded throughout the value chain. Supply chain decarbonization requires firms to identify emission-intensive activities, improve carbon visibility, redesign sourcing and logistics systems, coordinate environmental targets with suppliers, and integrate sustainability considerations into procurement, production, distribution, and product-development decisions. The development of supply chain decarbonization strategies has accordingly been framed as a process requiring a combination of strategic objectives, technological modernization, carbon accounting, collaboration, operational restructuring, and continuous performance assessment [4]. Evidence from recent supply chain research similarly indicates that innovation alone is insufficient unless firms establish mechanisms for supply chain collaboration and mapping that allow carbon-intensive processes and relationships to be identified and addressed across organizational boundaries [5]. These findings highlight an important transition from firm-level carbon management toward network-level decarbonization, in which operational and environmental performance increasingly depends on the ability of interconnected organizations to exchange information and coordinate strategic action.

This challenge is especially consequential for mechatronics supply chains. Mechatronics combines mechanical engineering, electronics, control systems, software, automation, sensors, embedded computing, robotics, and increasingly artificial intelligence within integrated products and production processes. The corresponding supply chains are technically complex and typically involve multiple tiers of suppliers providing electronic components, metals, precision mechanical parts, control equipment, batteries, semiconductors, sensors, software-enabled systems, and specialized manufacturing services. Such complexity creates substantial opportunities for technological innovation but simultaneously makes carbon management difficult because emissions are distributed across heterogeneous suppliers, manufacturing processes, energy systems, logistics networks, and product life cycles. The decarbonization of industries closely connected to mechatronics illustrates this interdependence. Research on green steel supply chains, for example, demonstrates that low-carbon transformation depends not only on changing steel-production technologies but also on trade structures, material sourcing, industrial coordination, and the behavior of downstream users such as the automotive sector [6, 7]. Similarly, the growing electrification of road transport has made battery supply security and associated supply chain strategies central to the broader transition toward decarbonized transportation systems [8]. For mechatronics-intensive industries, therefore, reducing carbon emissions requires attention to both the technological configuration of production and the wider architecture through which materials, components, information, energy, and products move across the supply chain.

Sectoral evidence further demonstrates that decarbonization pathways vary substantially according to industrial structure, technological maturity, capital intensity, and infrastructure requirements. In the cement industry, for instance, progress toward lower emissions is constrained by technological, economic, and policy barriers, indicating that technically feasible mitigation options may still face major adoption challenges in actual industrial contexts [9]. Similar evidence from oil refining shows that industrial decarbonization cannot be understood exclusively as an engineering problem because technological innovation interacts with sociotechnical systems, institutional arrangements, industrial practices, and policy environments [10]. Research on buildings has likewise identified sociotechnical barriers that can slow the adoption of decarbonization measures even where technically viable solutions exist, emphasizing the importance of organizational routines, stakeholder behavior, investment structures, skills, and coordination [11]. These observations are particularly relevant to mechatronics supply chains because organizations in this domain frequently operate at the intersection of capital-intensive equipment, technologically sophisticated production systems, complex supplier networks, and rapidly evolving digital infrastructures. Decarbonization in such contexts therefore requires firms to develop integrated strategies capable of linking technical innovation with organizational and supply chain transformation.

One of the most important opportunities for achieving such integration lies in digital technology adoption. Advanced digital technologies can substantially improve the visibility, traceability, predictability, and controllability of industrial operations. Technologies such as the Internet of Things, industrial sensors, artificial intelligence, machine learning, cloud platforms, big-data analytics, digital twins, automated systems, and integrated enterprise information systems allow organizations to collect and analyze detailed operational data in real time. In a decarbonization context, these technologies can support energy monitoring, predictive maintenance, process optimization, production scheduling, carbon accounting, transportation planning, material traceability, and supplier evaluation. Digital technologies can therefore improve not only operational efficiency but also the organization's capacity to identify where emissions occur and determine which interventions are likely to generate the greatest environmental benefits. The potential value of advanced analytical and simulation approaches is demonstrated in freight transportation research, where agent-based simulation integrated with mode-choice modeling has been applied to planning and decarbonization analysis, enabling decision-makers to evaluate the emissions implications of alternative transportation configurations [12]. Such capabilities are especially relevant to complex mechatronics networks, where decisions concerning sourcing, production, transport, inventory, and component flows can have interconnected environmental consequences.

Nevertheless, the presence of digital technologies does not automatically produce decarbonization. Technology creates informational and analytical capacity, but its environmental value depends on how organizations use that capacity to transform operational practices. This distinction is critical because firms may adopt digital systems primarily for productivity, automation, quality control, or cost reduction without systematically incorporating carbon considerations into operational decisions. Strategic decarbonization therefore requires the conversion of digital capability into sustainable operations. Sustainable operations encompass energy efficiency, material productivity, waste reduction, cleaner production, circularity, sustainable procurement, low-carbon logistics, renewable energy utilization, and the integration of environmental criteria into routine production and supply chain decisions. Research examining new product development in the context of industrial decarbonization has shown that sustainability must be embedded into organizational processes and innovation decisions rather than treated only as an external environmental objective [13]. Similarly, research on dairy supply chains has emphasized the importance of combining current operational practices with emerging strategies across production and supply chain stages, reinforcing the idea that effective decarbonization requires coordinated interventions rather than isolated technological solutions [14].

The role of sustainable operations becomes even more important when viewed from a life-cycle and supply chain perspective. Operational decarbonization involves reducing emissions generated directly by manufacturing activities while also addressing energy consumption, material choice, transportation, waste, supplier practices, and product design. In freight systems, for example, decarbonization requires changes in transport technologies, modal structures, logistics planning, demand patterns, and system-level interactions, making it difficult to achieve substantial reductions through a single intervention [15]. The same principle applies to mechatronics supply chains, where a digitally optimized factory may still possess a high carbon footprint if suppliers depend on emission-intensive energy sources, components require carbon-intensive materials, transportation networks are inefficient, or product design does not account for life-cycle impacts. Consequently, sustainable operations provide the practical mechanism through which technological capabilities can be translated into measurable reductions in energy and resource consumption. From this perspective, digitalization functions as an enabling infrastructure, whereas sustainable operations represent the organizational routines and process-level actions through which decarbonization is operationalized.

Energy-system characteristics further shape the feasibility of industrial decarbonization. The transition toward low-carbon electricity, renewable energy, and flexible energy systems affects the carbon intensity of manufacturing, automation, electrified transportation, and digitally controlled production. Energy storage has been identified as an important component of power-system decarbonization because it can facilitate greater integration of variable renewable energy, improve system flexibility, and support reliability as conventional fossil-based generation is progressively displaced [16]. Economic evaluations of electricity-sector decarbonization similarly demonstrate that transition pathways must be assessed in terms of both environmental benefits and economic consequences, emphasizing that the feasibility of low-carbon strategies depends on the cost and structure of the wider energy system [17]. For mechatronics firms, the implications are substantial because advanced manufacturing, robotics, automation, data centers, intelligent control systems, and electrified production processes can be electricity intensive. Digitalization may increase operational efficiency, but its overall decarbonization contribution depends partly on whether energy inputs themselves are transitioning toward lower-carbon sources.

Industrial decarbonization also requires attention to economic complexity and structural transformation. Economies and industries characterized by sophisticated technological capabilities may possess greater capacity to develop, absorb, and diffuse advanced low-carbon technologies, but complexity can also increase coordination requirements across sectors and supply chains. Evidence regarding renewable energy and economic complexity indicates that structural characteristics of economies significantly influence their decarbonization trajectories [3]. At the firm level, comparable dynamics may be observed within mechatronics industries, where sophisticated technologies provide substantial opportunities for process optimization while simultaneously increasing dependence on specialized materials, advanced components, and globally interconnected suppliers. This duality means that decarbonization cannot be reduced to improving the environmental performance of individual production facilities. Rather, organizations require strategies capable of coordinating technological innovation, material flows, supplier relationships, operational standards, and low-carbon objectives throughout the supply network.

Supply chain integration is therefore likely to play a central role in translating sustainability ambitions into decarbonization performance. Integration involves the coordinated exchange of information, joint planning, aligned decision-making, traceability, collaborative problem-solving, and synchronization of processes between internal functions and external partners. In the context of decarbonization, these capabilities enable organizations to share carbon-related information with suppliers, identify emission hotspots, align environmental targets, improve material and logistics decisions, and coordinate investments in cleaner technologies. The importance of supply chain collaboration and mapping for decarbonization has been directly demonstrated, with recent evidence indicating that innovative supply chain practices generate stronger decarbonization outcomes when supported by collaborative structures and visibility across the network [5]. Similarly, conceptual work on supply chain decarbonization emphasizes that carbon reduction should be embedded in strategic supply chain management through coordinated planning, assessment, and transformation rather than implemented as a series of unconnected environmental projects [4]. For mechatronics supply chains, where multiple suppliers contribute technically specialized components and subsystems, the capacity to integrate environmental information across organizational boundaries may be particularly important.

Another increasingly important dimension of strategic decarbonization concerns human capital. Digital transformation, low-carbon manufacturing, energy-system innovation, and sustainable supply chain management require specialized competencies that cannot be created solely through investment in physical technology. Organizations need employees who are capable of interpreting carbon and energy data, operating digital monitoring systems, integrating sustainability metrics into engineering decisions, evaluating low-carbon technologies, and coordinating environmental objectives across functional and organizational boundaries. Research on workforce development for decarbonization has highlighted the importance of reskilling and upskilling, including targeted micro-credential programs designed to prepare workers for changing technological and energy-sector requirements [18]. The human-capability dimension is especially salient in mechatronics because the field already depends on interdisciplinary expertise linking mechanical systems, electronics, software, automation, and control. Integrating decarbonization into such environments requires an additional layer of competency in sustainability analytics, energy management, carbon accounting, circularity, and sustainable supply chain design. Strategic decarbonization should therefore be viewed not only as a technology and operations challenge but also as an organizational-learning challenge.

Broader decarbonization research further indicates that successful transition pathways depend heavily on contextual conditions. Studies of environmentally oriented development pathways have demonstrated that decarbonization can interact with sectoral development, economic activity, and structural change in complex ways, making context-specific analysis necessary [19]. Likewise, comparisons across industrial sectors show that the technological options, costs, organizational barriers, and policy requirements associated with carbon reduction differ substantially according to the characteristics of each industry [9, 10]. These findings caution against assuming that generic decarbonization prescriptions can be transferred directly into highly specialized industrial settings. Mechatronics supply chains possess distinctive characteristics, including technological heterogeneity, intensive digitalization, complex component interdependence, high requirements for precision and reliability, and close relationships between product architecture and production technology. Understanding decarbonization in this context therefore requires empirical investigation of how digital capability, sustainable operations, and supply chain integration interact within the same strategic framework.

Despite rapid growth in the decarbonization literature, important fragmentation remains. Existing research has generated substantial knowledge concerning specific sectors such as steel [6, 7], cement [9], oil refining [10], transportation [8, 12, 15], power systems [16, 17], and food-related supply chains [14]. Other studies have concentrated on economic, governance, human-capital, or structural determinants of decarbonization [2, 3, 18]. Although these perspectives provide important insights, considerably less attention has been devoted to explaining how digital technologies, sustainable operational capabilities, and supply chain integration function together as complementary determinants of decarbonization within mechatronics supply chains. In particular, there is a need to move beyond examining whether digital technology is associated with environmental performance and instead determine through which organizational mechanisms digitalization produces carbon-reduction outcomes.

This distinction has substantial strategic implications. If digital technology directly reduces carbon emissions, organizations may prioritize investments in automation, analytics, sensing, and digital infrastructure as primary decarbonization instruments. If, however, the influence of digitalization occurs largely through sustainable operations and supply chain integration, technology investment alone is unlikely to be sufficient. Managers would instead need to ensure that digital information is translated into changes in energy use, materials, production planning, procurement, logistics, supplier collaboration, and carbon-oriented decision-making. The distinction is also important for assessing the sequence through which organizational capabilities develop. Digital technologies may first enable sustainable operational practices; these practices may strengthen supply chain coordination around environmental objectives; and greater integration may ultimately enhance strategic decarbonization. Such a sequential capability-building process is consistent with the broader understanding of decarbonization as a systems transition requiring coordinated technological, operational, organizational, and interorganizational changes rather than a single technical intervention [1, 11].

Accordingly, examining direct and indirect relationships among digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization can contribute to both theory and managerial practice. Theoretically, such an approach integrates technological capability, sustainable operations, and supply chain perspectives within a unified explanatory model of industrial decarbonization. Managerially, it can help organizations determine where investments and organizational interventions should be concentrated to generate the greatest carbon-reduction benefits. This is particularly relevant in emerging industrial contexts where firms may face simultaneous pressures to modernize production, digitalize supply chains, reduce energy and material costs, enhance competitiveness, and respond to growing environmental expectations. Strategic decarbonization under these conditions requires more than adopting environmentally desirable technologies; it requires organizations to create coherent operational and supply chain architectures through which technological capabilities are converted into measurable environmental outcomes.

Therefore, the aim of this study was to investigate the direct and indirect effects of digital technology adoption, sustainable operations, and supply chain integration on strategic decarbonization in mechatronics supply chains in Tehran, with particular emphasis on the mediating and sequential mechanisms through which digital capabilities are transformed into low-carbon operational and supply chain outcomes.

2. Methodology

This study employed a quantitative, applied, cross-sectional research design to examine the mechanisms through which digital technologies and sustainable operations contribute to strategic decarbonization within mechatronics supply chains. The research framework was developed on the premise that decarbonization in technologically intensive manufacturing environments is not merely a consequence of isolated environmental initiatives but rather results from the coordinated deployment of digital capabilities, sustainable operational practices, supply chain integration, and carbon-oriented strategic decision-making. Accordingly, the study was designed to empirically investigate the relationships among digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization performance in organizations operating within mechatronics-related supply chains. The statistical population consisted of managers, engineers, supply chain specialists, operations and production professionals, sustainability personnel, logistics experts, procurement specialists, and information technology professionals working in mechatronics, industrial automation, electronics, automotive components, precision manufacturing, robotics, control systems, and related technology-intensive manufacturing companies located in Tehran, Iran. Participants were required to have direct professional involvement in at least one area related to supply chain management, manufacturing operations, digital transformation, environmental management, energy management, logistics, procurement, production planning, or sustainability initiatives. To ensure that respondents possessed sufficient organizational and technical knowledge to evaluate the study constructs, inclusion criteria required a minimum of two years of relevant professional experience and current employment in a position involving operational, technical, managerial, or supply chain responsibilities. Individuals with exclusively administrative responsibilities and no direct knowledge of the organization’s production, logistics, digitalization, sustainability, or supply chain activities were excluded from participation. Using a purposive sampling strategy supplemented by proportional organizational recruitment, 348 questionnaires were distributed among eligible professionals working in selected mechatronics-related manufacturing and technology companies in Tehran. A total of 326 questionnaires were returned. Following data screening, 14 questionnaires were excluded because of substantial missing responses, response-pattern irregularities, or incomplete measurement sections. Consequently, data obtained from exactly 312 participants were retained for the final statistical analyses. Participation was voluntary, and respondents were informed about the objectives of the research, the confidentiality of their responses, and the use of the collected information exclusively for scientific purposes. No personally identifiable information was included in the analytical dataset. The sample size was considered adequate for multivariate analysis and structural equation modeling because it exceeded the minimum requirements based on both the number of latent constructs included in the proposed model and the number of structural relationships directed toward the principal endogenous variables.

Data were collected using a structured questionnaire developed to operationalize the principal dimensions of digitalization, sustainable operations, supply chain integration, and strategic decarbonization within the context of mechatronics supply chains. The questionnaire consisted of two main sections. The first section collected general professional and organizational information, including respondents’ professional position, years of work experience, organizational function, organizational size, and principal area of industrial activity. The second section contained the measurement items related to the conceptual variables of the study. All construct items were assessed using a five-point Likert scale ranging from 1, representing “strongly disagree,” to 5, representing “strongly agree.” Digital technology adoption was assessed in terms of the extent to which organizations incorporated advanced digital technologies into supply chain and operational processes. The measurement domain included the application of Internet of Things technologies and industrial sensors, artificial intelligence and machine learning, big-data analytics, cloud-based information systems, digital supply chain platforms, enterprise resource planning integration, real-time monitoring systems, digital twins, smart manufacturing technologies, automated production and logistics systems, and digitally enabled traceability. Particular attention was given to whether these technologies were used merely for automation or whether they generated actionable information for resource optimization, energy management, supplier coordination, production planning, logistics efficiency, predictive maintenance, and carbon-related decision-making. Sustainable operations were measured through items addressing energy efficiency, resource productivity, waste minimization, circular production practices, sustainable procurement, low-carbon logistics, environmentally responsible production planning, material efficiency, product-life-cycle considerations, recycling and reuse, cleaner production, renewable or lower-carbon energy utilization, and environmental criteria in supplier and process selection. The sustainable operations construct was therefore conceptualized as the organization's systematic integration of environmental considerations into routine manufacturing and supply chain decisions rather than as a collection of isolated environmental projects.

Supply chain integration was evaluated through items measuring internal functional coordination as well as external collaboration with suppliers, logistics partners, technology providers, and customers. These items addressed information sharing, interoperability of digital systems, visibility across supply chain stages, collaborative planning, supplier involvement in environmental initiatives, coordination of production and logistics activities, traceability of materials and components, joint problem-solving, and the integration of environmental and carbon-related information into interorganizational decision-making. Strategic decarbonization was operationalized as the organization's systematic capacity to reduce carbon emissions and carbon intensity across manufacturing and supply chain activities while maintaining operational and competitive performance. The corresponding items assessed the existence of explicit carbon-reduction objectives, incorporation of emissions considerations into strategic decisions, measurement and monitoring of operational and supply chain emissions, implementation of energy- and carbon-efficiency programs, supplier decarbonization initiatives, low-carbon transportation and logistics practices, redesign of processes to reduce energy and material consumption, and achievement of measurable reductions in emissions intensity. Because decarbonization represents both an environmental objective and a strategic organizational capability, the measurement instrument also assessed the degree to which carbon-reduction considerations were embedded in investment decisions, technology selection, supplier evaluation, process improvement, and long-term operations planning.

The preliminary questionnaire was evaluated by a panel of academic and industry experts with expertise in supply chain management, industrial engineering, mechatronics, sustainable manufacturing, operations management, digital transformation, and environmental management to establish content validity and ensure that the items adequately represented the industrial context under investigation. Based on expert evaluations, items characterized by conceptual overlap, unclear terminology, or insufficient relevance to mechatronics supply chains were revised or removed. Particular attention was paid to differentiating general digitalization from the strategic utilization of digital information for environmental and carbon management. A pilot administration was subsequently conducted with a small group of professionals with characteristics comparable to those of the main study population in order to assess item clarity, questionnaire completion procedures, and preliminary internal consistency. The pilot responses were not included in the final dataset. The wording of several items was refined following the pilot assessment to improve technical clarity and minimize ambiguity. In the final measurement assessment, internal consistency was examined using Cronbach's alpha and composite reliability, while convergent validity was evaluated through standardized factor loadings and average variance extracted. Cronbach's alpha and composite reliability coefficients of 0.70 or higher were considered indicative of acceptable reliability, whereas an average variance extracted value of at least 0.50 was considered evidence of adequate convergent validity. Indicator loadings were examined to determine whether individual items adequately represented their respective latent variables. Discriminant validity was evaluated by examining the distinctiveness of the constructs using the heterotrait-monotrait ratio and interconstruct relationships, ensuring that digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization represented empirically distinguishable dimensions of the proposed model.

Data analysis was conducted through a sequential procedure consisting of data screening, descriptive analysis, measurement-model assessment, and structural-model evaluation. Initially, the dataset was examined for missing values, incomplete questionnaires, extreme response patterns, multivariate outliers, and potential data-entry errors. Questionnaires with substantial missing data or evidence of non-engaged response behavior were excluded before the principal analyses. Descriptive statistics were then calculated to summarize participant characteristics and provide an overview of the distributions of the main research variables. Means, standard deviations, minimum and maximum values, skewness, and kurtosis were examined for the principal constructs. Correlation coefficients were calculated to evaluate the direction and preliminary strength of the relationships among digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization. Potential multicollinearity was assessed using variance inflation factor values to ensure that excessive correlations among predictor variables did not compromise the estimation of the structural relationships. Harman's single-factor procedure and examination of the latent-variable correlation structure were additionally used as diagnostic procedures to assess the potential influence of common method variance resulting from the use of a self-report questionnaire administered at a single point in time.

Partial least squares structural equation modeling was employed as the principal analytical technique because the proposed research model focused simultaneously on prediction, explanation of variance in strategic decarbonization, and estimation of relationships among multiple latent constructs. The analytical procedure was conducted in two stages. First, the measurement model was assessed by examining indicator reliability, internal consistency reliability, convergent validity, and discriminant validity. Standardized outer loadings, Cronbach's alpha, composite reliability, and average variance extracted were calculated for each latent construct. Indicators with sufficiently strong standardized loadings were retained, while potentially weak indicators were evaluated on the basis of both their statistical performance and their conceptual contribution to content validity. Discriminant validity was examined primarily through heterotrait-monotrait ratios, with values below commonly accepted thresholds interpreted as evidence that the constructs measured theoretically distinct phenomena. Variance inflation factors were also calculated at both the indicator and structural levels to identify possible collinearity problems. Following confirmation of satisfactory measurement quality, the structural model was assessed by estimating standardized path coefficients between the latent variables. The model examined the direct contribution of digital technology adoption to strategic decarbonization, the contribution of sustainable operations to strategic decarbonization, the relationship between digital technology adoption and sustainable operations, and the role of supply chain integration in translating technological and operational capabilities into improved decarbonization outcomes.

The statistical significance of the structural paths was determined through a nonparametric bootstrapping procedure using 5,000 resamples, from which standard errors, t statistics, p values, and confidence intervals were obtained. Relationships were considered statistically significant at $p < 0.05$. In addition to statistical significance, effect sizes were examined to evaluate the substantive contribution of each predictor to the endogenous constructs. The coefficient of determination was used to determine the proportion of variance explained in sustainable operations, supply chain integration, and strategic decarbonization, while effect-size statistics were evaluated to determine the incremental explanatory contribution of individual predictors. Predictive relevance was assessed to determine whether the proposed model possessed meaningful out-of-sample predictive capability for the endogenous constructs. Indirect effects were additionally estimated to investigate whether sustainable operations and supply chain integration functioned as mechanisms through which digital technology adoption contributed to strategic decarbonization. Bootstrapped confidence intervals were used to assess these indirect relationships rather than relying exclusively on sequential significance testing. This analytical strategy made it possible to distinguish between the direct technological contribution to decarbonization and the indirect contribution generated when digital capabilities were converted into sustainable operational practices and integrated supply chain processes. The final interpretation of the model was based on the magnitude, direction, statistical significance, explanatory power, effect sizes, and predictive relevance of the estimated relationships, thereby providing a comprehensive empirical assessment of how digital technologies and sustainable operations jointly support strategic decarbonization in mechatronics supply chains.

3. Findings and Results

The final analytical sample consisted of 312 professionals employed in mechatronics-related manufacturing, industrial automation, electronics, automotive component manufacturing, robotics, control systems, precision manufacturing, and related technology-intensive industries in Tehran. Of the participants, 198 (63.5%) were men and 114 (36.5%) were women. In terms of age, 48 participants (15.4%) were younger than 30 years, 126 (40.4%) were between 30 and 39 years, 92 (29.5%) were between 40 and 49 years, and 46 (14.7%) were aged 50 years or older. Regarding educational attainment, 34 participants (10.9%) held an associate degree or diploma-level qualification, 138 (44.2%) held a bachelor's degree, 116 (37.2%) held a master's degree, and 24 (7.7%) held a doctoral degree. Participants represented a range of occupational responsibilities directly related to the study context. Specifically, 61 participants (19.6%) were involved primarily in production and operations management, 55 (17.6%) worked in supply chain, procurement, or logistics positions, 49 (15.7%) were employed in engineering and technical functions, 42 (13.5%) worked in information technology, digital transformation, or automation-related roles, 38 (12.2%) held sustainability, environmental management, or energy-management responsibilities, and 67 (21.5%) occupied senior or middle-management positions involving multiple operational functions. With respect to professional experience, 57 participants (18.3%) had between 2 and 5 years of relevant experience, 98 (31.4%) had between 6 and 10 years, 91 (29.2%) had between 11 and 15 years, and 66 (21.2%) had more than 15 years of professional experience. The broad distribution of participants across technical, managerial, operational, sustainability, and supply chain functions provided an appropriate empirical basis for evaluating digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization from multiple organizational perspectives.

Table 1. Descriptive Statistics and Correlations Among the Main Study Variables

Variable	Mean	SD	Skewness	Kurtosis	1	2	3	4
1. Digital Technology Adoption	3.74	0.69	-0.41	-0.18	1.00			
2. Sustainable Operations	3.62	0.65	-0.33	-0.11	0.61**	1.00		
3. Supply Chain Integration	3.57	0.71	-0.28	-0.36	0.56**	0.64**	1.00	
4. Strategic Decarbonization	3.48	0.68	-0.22	-0.27	0.59**	0.71**	0.68**	1.00

As shown in Table 1, the mean scores of all four principal constructs were above the theoretical midpoint of the five-point response scale, indicating that the participating organizations demonstrated moderate-to-relatively-high levels of digitalization, sustainable operational practices, interorganizational supply chain integration, and strategic decarbonization activity. Digital technology adoption had the highest mean score ($M = 3.74$, $SD = 0.69$), suggesting that the use of digital platforms, industrial sensors, analytics, automation, and interconnected information technologies was comparatively well established among the organizations represented in the study. Sustainable operations also demonstrated a relatively high mean value ($M = 3.62$, $SD = 0.65$), followed by supply chain integration ($M = 3.57$, $SD = 0.71$) and strategic decarbonization ($M = 3.48$, $SD = 0.68$). The comparatively lower mean for strategic decarbonization suggests that although digital and operational capabilities were already present to a considerable extent, their complete translation into systematic carbon-reduction outcomes remained less developed. Skewness values ranged from -0.41 to -0.22 and kurtosis values ranged from -0.36 to -0.11, indicating no substantial distributional abnormalities. The correlation analysis further demonstrated statistically significant positive relationships among all principal variables. Digital technology adoption was positively related to sustainable operations ($r = 0.61$, $p < 0.01$), supply chain integration ($r = 0.56$, $p < 0.01$), and strategic decarbonization ($r = 0.59$, $p < 0.01$). Sustainable operations demonstrated the strongest bivariate association with strategic decarbonization ($r = 0.71$, $p < 0.01$), while supply chain integration was also strongly associated with strategic decarbonization ($r = 0.68$, $p < 0.01$). The positive and statistically significant interconstruct correlations were consistent with the proposed theoretical model while remaining sufficiently below levels that would ordinarily indicate problematic construct redundancy or severe multicollinearity.

Table 2. Measurement Model Reliability and Convergent Validity

Construct	Indicator	Standardized Loading	Cronbach's Alpha	Composite Reliability	AVE
Digital Technology Adoption	DTA1	0.78	0.90	0.92	0.62
	DTA2	0.82			
	DTA3	0.84			
	DTA4	0.76			
	DTA5	0.81			
	DTA6	0.73			
Sustainable Operations	SO1	0.79	0.91	0.93	0.66
	SO2	0.83			
	SO3	0.86			
	SO4	0.80			
	SO5	0.78			

	SO6	0.81			
Supply Chain Integration	SCI1	0.77	0.89	0.92	0.65
	SCI2	0.82			
	SCI3	0.84			
	SCI4	0.79			
	SCI5	0.81			
Strategic Decarbonization	SD1	0.80	0.92	0.94	0.68
	SD2	0.85			
	SD3	0.83			
	SD4	0.87			
	SD5	0.81			
	SD6	0.78			

The measurement-model results presented in Table 2 demonstrated satisfactory indicator reliability, internal consistency, and convergent validity across all four latent constructs. Standardized indicator loadings for digital technology adoption ranged from 0.73 to 0.84, while the corresponding loadings for sustainable operations ranged from 0.78 to 0.86. Supply chain integration indicators showed loadings between 0.77 and 0.84, and the indicators representing strategic decarbonization ranged between 0.78 and 0.87. Thus, all retained indicators exceeded the commonly accepted minimum criterion of 0.70 and demonstrated adequate representation of their corresponding latent constructs. Cronbach's alpha coefficients ranged from 0.89 for supply chain integration to 0.92 for strategic decarbonization, indicating strong internal consistency reliability. Composite reliability coefficients similarly ranged from 0.92 to 0.94 and therefore exceeded the recommended threshold of 0.70. Convergent validity was also supported because the average variance extracted values were 0.62 for digital technology adoption, 0.66 for sustainable operations, 0.65 for supply chain integration, and 0.68 for strategic decarbonization. All AVE values were therefore above the minimum criterion of 0.50, demonstrating that each latent construct explained more than half of the variance in its indicators. Collectively, these results indicated that the measurement instrument demonstrated sufficient psychometric quality to proceed to the assessment of discriminant validity and structural relationships.

Table 3. Discriminant Validity Based on the Heterotrait-Monotrait Ratio

Construct	Digital Technology Adoption	Sustainable Operations	Supply Chain Integration	Strategic Decarbonization
Digital Technology Adoption	—			
Sustainable Operations	0.68	—		
Supply Chain Integration	0.63	0.72	—	
Strategic Decarbonization	0.66	0.79	0.76	—

The discriminant-validity analysis presented in Table 3 provided further evidence that the four latent variables represented empirically distinguishable dimensions. The heterotrait-monotrait ratios ranged from 0.63 to 0.79, and all values remained below the conservative threshold of 0.85. The lowest HTMT value was observed between digital technology adoption and supply chain integration (HTMT = 0.63), while the highest value occurred between sustainable operations and strategic decarbonization (HTMT = 0.79). Although the latter relationship was comparatively strong, it remained well within the acceptable range and was theoretically consistent with the close conceptual connection between environmentally responsible operational practices and carbon-reduction outcomes. The HTMT ratio between digital technology adoption and strategic decarbonization was 0.66, while the ratio between supply chain integration and strategic decarbonization was 0.76. These findings indicated that the constructs were related but not statistically interchangeable. Consequently, the model demonstrated adequate discriminant validity, supporting the interpretation that digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization represented distinct organizational capabilities rather than alternative measurements of the same underlying phenomenon.

Table 4. Structural Model, Direct Effects, Indirect Effects, and Explanatory Power

Structural Relationship	β	SE	t	p	95% CI	f²	Result
Digital Technology Adoption → Sustainable Operations	0.61	0.047	12.98	<0.001	[0.518, 0.699]	0.59	Significant
Digital Technology Adoption → Supply Chain Integration	0.31	0.052	5.96	<0.001	[0.209, 0.410]	0.12	Significant
Sustainable Operations → Supply Chain Integration	0.45	0.049	9.18	<0.001	[0.353, 0.545]	0.26	Significant
Digital Technology Adoption → Strategic Decarbonization	0.18	0.045	4.00	<0.001	[0.093, 0.269]	0.06	Significant
Sustainable Operations → Strategic Decarbonization	0.42	0.051	8.24	<0.001	[0.320, 0.518]	0.24	Significant
Supply Chain Integration → Strategic Decarbonization	0.31	0.048	6.46	<0.001	[0.218, 0.403]	0.15	Significant
Digital Technology Adoption → Sustainable Operations → Strategic Decarbonization	0.26	0.039	6.67	<0.001	[0.188, 0.340]	—	Significant
Digital Technology Adoption → Supply Chain Integration → Strategic Decarbonization	0.10	0.024	4.17	<0.001	[0.057, 0.151]	—	Significant
Digital Technology Adoption → Sustainable Operations → Supply Chain Integration → Strategic Decarbonization	0.09	0.021	4.29	<0.001	[0.052, 0.135]	—	Significant

The structural-model results shown in Table 4 supported all of the principal relationships specified in the research framework. Digital technology adoption demonstrated a strong positive effect on sustainable operations ($\beta = 0.61$, SE = 0.047, $t = 12.98$, $p < 0.001$), indicating that organizations with more extensive use of digitally enabled production systems, advanced analytics, automation, real-time monitoring, integrated information platforms, and related technologies also reported stronger implementation of energy-efficiency, resource-efficiency, waste-reduction, circularity, sustainable procurement, and low-carbon operational practices. The effect size associated with this relationship was substantial ($f^2 = 0.59$), indicating that digital technology adoption represented an important explanatory factor in the development of sustainable operational capabilities. Digital technology adoption also exerted a statistically significant positive direct effect on supply chain integration ($\beta = 0.31$, SE = 0.052, $t = 5.96$, $p < 0.001$), demonstrating that digitalization contributed to improved information sharing, visibility, traceability, interoperability, and coordination across supply chain actors. Sustainable operations independently contributed to supply chain integration ($\beta = 0.45$, SE = 0.049, $t = 9.18$, $p < 0.001$), suggesting that organizations pursuing sustainable production and resource-management practices were also more likely to coordinate environmental objectives, operational data, and decision-making processes with suppliers and other external partners. Together, digital technology adoption and sustainable operations explained 49% of the variance in supply chain integration, indicating considerable explanatory power.

The results further showed that all three principal predictors exerted statistically significant direct effects on strategic decarbonization. Digital technology adoption had a positive direct effect on strategic decarbonization ($\beta = 0.18$, SE = 0.045, $t = 4.00$, $p < 0.001$), confirming that digital capabilities independently supported carbon-reduction performance even after sustainable operations and supply chain integration were incorporated into the structural model. However, this direct effect was smaller than the corresponding effects of sustainable operations and supply chain integration, indicating that digitalization alone was not the dominant mechanism through which decarbonization outcomes were achieved. Sustainable operations exerted the strongest direct effect on strategic decarbonization ($\beta = 0.42$, SE = 0.051, $t = 8.24$, $p < 0.001$), with an effect size of $f^2 = 0.24$. This finding demonstrated that systematic improvements in energy efficiency, resource productivity, waste reduction, sustainable procurement, cleaner production, and low-carbon logistics were central determinants of decarbonization performance. Supply chain integration also had a substantial direct effect on strategic decarbonization ($\beta = 0.31$, SE = 0.048, $t = 6.46$, $p < 0.001$), demonstrating that greater coordination, information exchange, supplier collaboration, and supply-chain-wide environmental visibility were associated with stronger carbon-reduction outcomes. Collectively, digital technology adoption, sustainable operations, and supply chain integration explained 68% of the variance in strategic decarbonization, indicating strong explanatory power for the proposed model.

The mediation analysis provided additional insight into the mechanisms underlying these relationships. The indirect effect of digital technology adoption on strategic decarbonization through sustainable operations was positive and statistically significant ($\beta = 0.26$, SE = 0.039, $t = 6.67$, $p < 0.001$, 95% CI [0.188, 0.340]). Because the confidence interval did not include zero, sustainable operations significantly mediated the relationship between digital technology adoption and strategic decarbonization. This finding suggested that a substantial proportion of the decarbonization benefit associated with digital technologies emerged when digital capabilities were converted into concrete changes in energy use, material efficiency, waste reduction, production planning, procurement, and environmental performance management. A second statistically significant indirect effect was observed through supply chain integration ($\beta = 0.10$, SE = 0.024, $t = 4.17$, $p < 0.001$), indicating that digital technologies also contributed to decarbonization by strengthening coordination, transparency, and information exchange across organizational and supply chain boundaries. In addition, the sequential indirect pathway from digital technology adoption through sustainable operations and subsequently supply chain integration to strategic decarbonization was significant ($\beta = 0.09$, SE = 0.021, $t = 4.29$, $p < 0.001$). This sequential effect indicated that digital technologies first enhanced sustainable operational capability, which subsequently facilitated greater supply chain integration and ultimately contributed to stronger strategic decarbonization outcomes. Because the direct effect of digital technology adoption on strategic decarbonization remained statistically significant after the mediating variables were introduced, the findings were consistent with partial rather than complete mediation.

The explanatory and predictive indicators further supported the adequacy of the proposed structural model. Digital technology adoption explained 37% of the variance in sustainable operations, while digital technology adoption and sustainable operations jointly explained 49% of the variance in supply chain integration. Most importantly, the full model explained 68% of the variance in strategic decarbonization, indicating that the combined technological, operational, and relational capabilities incorporated into the model accounted for a substantial proportion of organizational differences in decarbonization performance. The predictive relevance values were greater than zero for all endogenous constructs, with $Q^2 = 0.23$ for sustainable operations, $Q^2 = 0.31$ for supply chain integration, and $Q^2 = 0.46$ for strategic decarbonization. These values demonstrated that the model possessed meaningful predictive relevance in addition to explanatory power. Variance inflation factor values for the structural predictors ranged from 1.54 to 2.36 and therefore remained below commonly accepted thresholds, indicating that multicollinearity did not materially affect the estimation of the structural paths. The combination of significant path coefficients, substantial explained variance, acceptable effect sizes, statistically significant mediation effects, and positive predictive-relevance indices provided consistent evidence in support of the proposed conceptual framework.

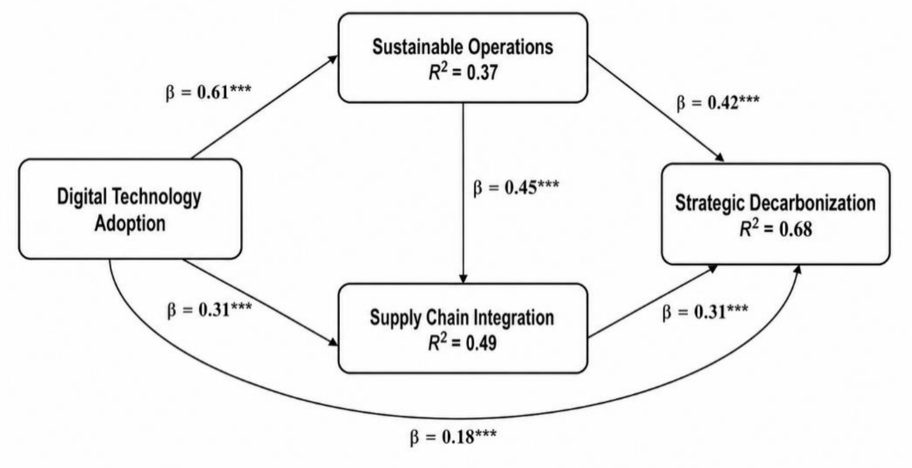

Figure 1. Structural Model of Digital Technology Adoption, Sustainable Operations, Supply Chain Integration, and Strategic Decarbonization in Mechatronics Supply Chains

Figure 1 summarizes the final structural model and illustrates the pattern of direct and indirect relationships identified in the empirical analysis. The strongest structural path was observed from digital technology adoption to sustainable operations (β = 0.61), demonstrating that digital capability constituted an important foundation for environmentally sustainable operational transformation. Sustainable operations, in turn, exerted the strongest direct influence on strategic decarbonization (β = 0.42), followed by supply chain integration (β = 0.31) and digital technology adoption (β = 0.18). The model therefore indicated that digital transformation contributed to decarbonization through both direct and capability-building mechanisms. Digital technologies generated the infrastructure for visibility, analytics, monitoring, automation, and data-based decision-making, but stronger carbon-reduction outcomes emerged when these capabilities were translated into sustainable production practices and coordinated across organizational boundaries. The significant sequential pathway from digital technology adoption to sustainable operations, from sustainable operations to supply chain integration, and ultimately from supply chain integration to strategic decarbonization further demonstrated that technological investments were most effective when embedded in broader operational and interorganizational transformations. Taken together, the findings indicate that strategic decarbonization in mechatronics supply chains is not driven by digitalization, sustainable operations, or collaboration independently; rather, it emerges from the interaction of these complementary organizational capabilities within an integrated low-carbon supply chain strategy.

4. Discussion and Conclusion

The present study examined the relationships among digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization in mechatronics supply chains. The findings demonstrated that digital technology adoption had a strong positive effect on sustainable operations, digital technology adoption and sustainable operations both contributed significantly to supply chain integration, and all three principal constructs were positively associated with strategic decarbonization. Sustainable operations emerged as the strongest direct predictor of strategic decarbonization, followed by supply chain integration and digital technology adoption. The model also revealed significant indirect effects, showing that digital technology adoption influenced strategic decarbonization through sustainable operations, through supply chain integration, and through the sequential pathway of sustainable operations followed by supply chain integration. Collectively, the model explained a substantial proportion of the variance in strategic decarbonization, indicating that low-carbon transformation in mechatronics supply chains is best understood as an integrated process in which technological capability, operational sustainability, and interorganizational coordination reinforce one another.

One of the most important findings was the strong positive effect of digital technology adoption on sustainable operations. This result suggests that organizations with more advanced use of digital technologies, including sensors, integrated information systems, automation, analytics, real-time monitoring, and digitally enabled coordination, are better positioned to implement sustainable operational practices. In practical terms, digitalization appears to improve the capability of firms to monitor energy consumption, identify waste, optimize resource use, detect inefficiencies, schedule production more effectively, and incorporate environmental indicators into operational decision-making. This finding is consistent with the broader logic of decarbonization pathways, which emphasizes the role of technological modernization in enabling firms and economies to move toward lower-carbon forms of production [1]. It also aligns with evidence showing that industrial decarbonization requires not only cleaner technologies but also improved systems for managing and coordinating technological and operational change [10]. In this sense, digital technologies appear to function as an enabling infrastructure through which sustainability objectives can be translated into more precise and responsive operational actions.

The strength of the relationship between digital technology adoption and sustainable operations can also be interpreted in light of the increasing importance of data-driven environmental management. In highly complex industrial systems, sustainability improvements depend heavily on the ability to observe and analyze operational processes at a granular level. Advanced digital technologies can reveal previously hidden inefficiencies in energy consumption, equipment utilization, logistics flows, and material use. Research on freight decarbonization has demonstrated that analytical and simulation-based approaches can improve the evaluation of transport alternatives and support lower-carbon planning decisions [12]. Similarly, studies of energy-system decarbonization highlight the importance of system flexibility, information, and optimization in supporting low-carbon transitions [16]. These perspectives support the present finding that digital capability contributes meaningfully to sustainable operations because it enhances organizational visibility, control, and responsiveness across production and supply chain processes.

The study also found that digital technology adoption had a significant positive effect on supply chain integration. This finding indicates that organizations with stronger digital capabilities are more likely to achieve higher levels of information sharing, traceability, coordination, and process synchronization across supply chain partners. This result is theoretically plausible because digital technologies reduce informational barriers and allow suppliers, manufacturers, logistics providers, and customers to access and exchange operational information in a more timely and structured manner. The finding is strongly supported by prior research emphasizing the importance of supply chain mapping and collaboration in decarbonization strategies [5]. It also aligns with conceptual work arguing that successful supply chain decarbonization depends on coordinated strategies, shared environmental objectives, and integrated decision-making across supply chain actors [4]. Therefore, digitalization appears to support decarbonization not only through internal efficiency gains but also by improving the relational infrastructure needed for collective environmental action.

Another notable finding was that sustainable operations significantly strengthened supply chain integration. This result suggests that firms pursuing sustainability more systematically are also more likely to collaborate with supply chain partners around environmental objectives. Sustainable operations often require the organization to move beyond its own production boundaries because decisions related to materials, supplier standards, transport modes, packaging, energy sources, and product design depend on external actors. As a result, sustainability initiatives can create a practical need for greater information exchange and coordination. This interpretation is consistent with findings from dairy supply chains, where decarbonization strategies require interventions across multiple stages of production and distribution rather than isolated action by one firm [14]. Similar conclusions can be drawn from freight transport research, which shows that decarbonization is shaped by system-level interactions and therefore depends on coordination among multiple stakeholders [15]. Accordingly, the present results indicate that sustainability-oriented operations may themselves act as a catalyst for deeper supply chain integration.

The strongest direct effect on strategic decarbonization was observed for sustainable operations. This finding indicates that organizations achieve the greatest improvements in carbon-reduction performance when sustainability principles are embedded directly into operational routines. In other words, strategic decarbonization appears to depend less on the mere existence of advanced technologies and more on how effectively firms alter their production, procurement, energy use, logistics, waste management, and resource-utilization practices. This finding is consistent with the argument that decarbonization must be operationalized through concrete changes in the way industrial activities are performed [1]. It also aligns with research demonstrating that industrial decarbonization requires integrated technological and operational interventions rather than reliance on isolated technical solutions [9, 10]. The present results therefore reinforce the view that sustainable operations constitute the core mechanism through which decarbonization objectives are converted into measurable environmental outcomes.

This result is further supported by research on industrial decarbonization in specific sectors. Studies of green steel supply chains have shown that meaningful reductions in industrial emissions depend on changes in material production, sourcing, trade, and downstream use rather than on incremental improvements alone [6, 7]. Similarly, research on new product development for industrial decarbonization indicates that sustainability must be incorporated into organizational innovation processes if meaningful carbon reductions are to be achieved [13]. These studies parallel the present finding because they demonstrate that carbon reduction becomes more effective when environmental objectives are embedded into routine operational and strategic decisions. For mechatronics supply chains, this implies that decarbonization depends on the systematic redesign of how materials, energy, components, equipment, and logistics are managed across the production system.

Supply chain integration also had a substantial positive effect on strategic decarbonization. This finding demonstrates that organizations are more successful in reducing carbon emissions when they possess stronger coordination and collaboration with suppliers and other supply chain partners. Because a large proportion of industrial emissions may originate outside the direct boundaries of the focal firm, decarbonization requires access to information about upstream and downstream activities. Supply chain integration can improve this visibility and enable organizations to coordinate carbon-reduction initiatives with suppliers, redesign logistics networks, select lower-carbon materials, and establish shared sustainability targets. The result aligns closely with recent evidence showing that supply chain collaboration and mapping enhance decarbonization outcomes by creating visibility and enabling coordinated action [5]. It is also consistent with the conceptual argument that supply chain decarbonization strategies require a network-level orientation rather than firm-level environmental management alone [4].

The direct effect of digital technology adoption on strategic decarbonization was positive but smaller than the effects of sustainable operations and supply chain integration. This pattern is important because it suggests that digitalization alone does not automatically create strong decarbonization outcomes. Instead, the primary value of digital technologies may lie in their capacity to enable operational transformation and supply chain coordination. This interpretation is consistent with the wider decarbonization literature, which has repeatedly emphasized that technological solutions are embedded within broader sociotechnical systems and therefore depend on organizational practices, institutional conditions, and behavioral factors [10, 11]. It is also compatible with research showing that even technically viable decarbonization options may face economic and organizational barriers that prevent their effective adoption [9]. The findings of the present study therefore caution against treating digital transformation as synonymous with decarbonization. Digital technologies become strategically meaningful for carbon reduction when they are connected to sustainability-oriented processes and collaborative supply chain structures.

The mediation analysis provides particularly strong support for this interpretation. Sustainable operations significantly mediated the relationship between digital technology adoption and strategic decarbonization. This means that part of the effect of digitalization on carbon reduction occurred because digital technologies strengthened the organization's ability to implement sustainable operational practices. This result is consistent with the notion that decarbonization is not produced by information and automation themselves but by the operational decisions made possible through them. Digital systems can identify energy inefficiencies, support predictive maintenance, optimize material flows, and improve production scheduling, but decarbonization occurs only when such information results in lower energy use, reduced waste, cleaner production, and improved resource efficiency. The finding is compatible with prior research emphasizing that technological and process innovation must be embedded within sustainable development pathways if they are to generate meaningful carbon reductions [1, 13].

Supply chain integration also significantly mediated the relationship between digital technology adoption and strategic decarbonization. This finding demonstrates that digital technologies contribute to decarbonization partly by facilitating greater coordination across supply chain actors. The result is highly consistent with recent research showing that supply chain innovation is more effective for decarbonization when accompanied by collaboration and mapping [5]. Digital platforms, traceability systems, and integrated databases can make carbon-related information more accessible throughout the supply chain, enabling suppliers and focal firms to identify emission hotspots and coordinate responses. This is especially important in mechatronics supply chains because environmental performance may depend on highly specialized upstream suppliers whose energy use, material selection, and manufacturing processes are not directly controlled by the focal firm.

The significant sequential mediation pathway from digital technology adoption to sustainable operations, then to supply chain integration, and finally to strategic decarbonization provides an even more comprehensive explanation of how low-carbon transformation may occur. This pathway suggests that digital capabilities first strengthen sustainability-oriented operational practices, which then create a need for greater interorganizational coordination, ultimately improving decarbonization performance. Such a sequence is theoretically consistent with systems approaches to decarbonization, where technological change, operational transformation, and network coordination are interdependent rather than isolated processes [1]. It is also consistent with sector-specific studies showing that decarbonization requires simultaneous changes in technologies, organizational routines, and supply chain structures [6, 14]. The sequential effect is particularly important because it implies that organizations may derive the greatest environmental benefit from digital transformation when they use technology not only to optimize internal processes but also to embed sustainability into supply chain relationships.

The substantial explanatory power of the model further reinforces the importance of this integrated perspective. The combined influence of digital technology adoption, sustainable operations, and supply chain integration explained a large proportion of the variance in strategic decarbonization. This finding suggests that the proposed constructs represent central organizational capabilities for low-carbon transformation in mechatronics supply chains. It also demonstrates that decarbonization is not adequately explained by a single factor. Instead, strong performance appears to emerge through the interaction of technological, operational, and relational dimensions. This interpretation is consistent with evidence showing that decarbonization pathways are influenced by multiple structural, institutional, economic, and technological factors [2, 3]. The present study extends this logic to the organizational level by showing that firms also require a portfolio of complementary capabilities rather than a single environmental intervention.

The findings are also relevant to the broader issue of energy transition. Because industrial digitalization and automation are increasingly electricity dependent, the carbon benefits of technological transformation are partly contingent on the carbon intensity of the energy system. Prior research has emphasized the importance of renewable energy and storage in supporting power-system decarbonization [16], while economic evaluations of electricity-sector transformation show that low-carbon transitions must be both technically and economically viable [17]. This broader energy context helps explain why sustainable operations exerted a stronger effect on decarbonization than digitalization alone. Firms may adopt advanced digital systems, but if operational processes continue to rely on carbon-intensive energy, inefficient materials, or emission-intensive logistics, the environmental benefits of digital transformation may remain limited.

The results also have implications for workforce capability. Successful integration of digital technologies and sustainability requires employees who can interpret operational data, manage digital systems, understand carbon metrics, and translate technical information into low-carbon decisions. Research on reskilling and upskilling for decarbonization emphasizes the importance of workforce development in enabling organizations to manage the transition toward more sustainable energy and industrial systems [18]. In mechatronics supply chains, where technical and digital complexity is already high, the need for interdisciplinary skills is likely to be even more pronounced. The effectiveness of digital technologies may therefore depend partly on whether organizations possess the human capital required to integrate engineering, operations, data analytics, and sustainability management.

Finally, the findings support the broader conclusion that strategic decarbonization should be understood as a coordinated transformation of industrial systems rather than a narrow environmental initiative. Evidence from transportation, energy, steel, buildings, cement, and other sectors consistently indicates that effective decarbonization requires combinations of technological innovation, structural change, operational redesign, policy support, and stakeholder coordination [8, 11, 19]. The present study contributes to this literature by showing that, within mechatronics supply chains, digitalization can serve as a foundational capability, but its decarbonization value is amplified when it is translated into sustainable operations and integrated across supply chain relationships. This integrated perspective offers a more realistic explanation of how firms can move from technological modernization toward measurable carbon reduction.

Several limitations should be considered when interpreting the findings of this study. First, the cross-sectional design does not permit definitive causal conclusions regarding the temporal relationships among digital technology adoption, sustainable operations, supply chain integration, and strategic decarbonization. Although the structural model was theoretically grounded and statistically supported, the direction of influence should be confirmed through longitudinal or experimental designs. Second, the study relied on self-reported data obtained from organizational professionals, which may be affected by perceptual bias, common method variance, or socially desirable responses, particularly for constructs related to sustainability performance. Third, the sample was drawn from mechatronics-related organizations in Tehran, and the institutional, technological, energy, and supply chain characteristics of this setting may limit the generalizability of the findings to other regions or national contexts. Fourth, the model focused primarily on organizational and supply chain capabilities and did not explicitly include contextual variables such as regulatory pressure, energy prices, organizational size, supply chain complexity, financial resources, or access to renewable energy. Finally, strategic decarbonization was measured through organizational perceptions rather than directly verified carbon-emission inventories, and future studies may benefit from combining perceptual measures with objective emissions data.

Future studies should examine the proposed relationships longitudinally in order to determine how digital transformation and sustainability capabilities evolve over time and whether improvements in digitalization precede measurable changes in carbon performance. Multi-country or multi-region comparative studies would also be valuable for identifying how regulatory conditions, energy systems, industrial maturity, and infrastructure influence the effectiveness of decarbonization strategies. Future research could incorporate objective indicators such as Scope 1, Scope 2, and Scope 3 emissions, energy intensity, carbon intensity per unit of output, renewable energy utilization, and logistics emissions to strengthen the measurement of strategic decarbonization. Additional mediators and moderators should also be explored, including green innovation capability, organizational learning, environmental culture, regulatory pressure, supply chain resilience, technological readiness, and absorptive capacity. It would also be useful to distinguish between specific digital technologies such as artificial intelligence, digital twins, Internet of Things systems, blockchain, cloud platforms, and advanced analytics rather than treating digital technology adoption as a single aggregated capability. Finally, future research could use multi-level designs that simultaneously examine firm-level operations, supplier-level characteristics, and supply-network structures in order to better capture the distributed nature of carbon emissions across complex mechatronics ecosystems.

Managers in mechatronics supply chains should avoid treating digital transformation and decarbonization as separate strategic agendas. Digital investments should be explicitly linked to environmental objectives so that data from sensors, enterprise systems, analytics platforms, and automated processes are used to identify energy inefficiencies, monitor emissions, optimize material flows, reduce waste, and support low-carbon production decisions. Organizations should also embed sustainability indicators into operational dashboards, procurement criteria, supplier evaluations, production planning, and logistics decisions. Because supply chain integration was found to be a major driver of strategic decarbonization, firms should strengthen collaboration with suppliers and logistics partners through shared environmental targets, interoperable information systems, carbon-data exchange, joint process improvement, and coordinated low-carbon innovation initiatives. Management should also prioritize workforce development by providing employees with training in digital systems, energy management, carbon accounting, sustainability analytics, and cross-functional decision-making. Finally, organizations should establish decarbonization governance mechanisms that connect executive strategy with operational implementation, ensuring that digital capability, sustainable operations, supplier collaboration, and measurable carbon-reduction targets are managed as components of one integrated transformation program.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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All procedures performed in this study were under the ethical standards.

References

[1] M. Fay, H. Stephane, V.-S. Adrien, R. Julie, N. Ulf, and K. Tom, *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. Washington: World Bank Group, 2015.

[2] I. Hamid, M. S. Alam, A. Kanwal, P. K. Jena, M. Murshed, and R. Alam, "Decarbonization pathways: the roles of foreign direct investments, governance, democracy, economic growth, and renewable energy transition," *Environ. Sci. Pollut. Control Ser.,* vol. 29, no. 33, pp. 49816-49831, 2022, doi: 10.1007/s11356-022-18935-3.

[3] A. C. Nuta, "The significance of economic complexity and renewable energy for decarbonization in Eastern European countries," *Energies,* vol. 17, no. 21, p. 5271, 2024, doi: 10.3390/en17215271.

[4] M. Hryhorak, O. Harmash, and H. Трушкіна, "Conceptual Principles for Formation of the Supply Chains' Decarbonization Strategies," *Electronic Scientific Journal Intellectualization of Logistics and Supply Chain Management #1 2020,* no. 18, pp. 47-64, 2023, doi: 10.46783/smart-scm/2023-18-5.

[5] M. Muhammad Shujaat, G. Angappa, K. Sharfuddin Ahmed, and M. Muhammad Faraz, "Decarbonization through supply chain innovation: Role of supply chain collaboration and mapping," *Journal of Cleaner Production,* vol. 507, p. 145492, 2025, doi: 10.1016/j.jclepro.2025.145492.

[6] J. Shen, Q. Zhang, and S. Tian, "Decarbonization pathways analysis and recommendations in the green steel supply chain of a typical steel end user—automotive industry," *Applied Energy,* vol. 377, 2025, doi: 10.1016/j.apenergy.2024.124711.
[7] Z. Li, M. Åhman, J. Algers, and L. J. Nilsson, "Decarbonizing the Asian steel industries through green Hot Briquetted Iron trade," *Resources, Conservation and Recycling,* vol. 219, 2025, doi: 10.1016/j.resconrec.2025.108275.
[8] L. Campbell, M. Häfner, X. Lu, M. Noussan, P. P. Raimondi, and E. Zhu, "Securing Decarbonized Road Transport – A Comparison of How EV Deployment Has Become a Critical Dimension of Battery Security Strategies for China, the EU, and the US," *SSRN Electronic Journal,* 2021, doi: 10.2139/ssrn.4017429.
[9] O. E. Ige and M. Kabeya, "Decarbonizing the Cement Industry: Technological, Economic, and Policy Barriers to CO2 Mitigation Adoption," *Clean Technologies,* vol. 7, no. 4, p. 85, 2025, doi: 10.3390/cleantechnol7040085.
[10] S. Griffiths, B. K. Sovacool, J. Kim, M. Bazilian, and J. M. Uratani, "Decarbonizing the Oil Refining Industry: A Systematic Review of Sociotechnical Systems, Technological Innovations, and Policy Options," *Energy Research & Social Science,* vol. 89, p. 102542, 2022, doi: 10.1016/j.erss.2022.102542.
[11] E. Heinz, B. K. Sovacool, T. A. Kwan, and V. Petit, "The Sociotechnical Barriers to the Decarbonization of Buildings," 2025, doi: 10.21203/rs.3.rs-5926332/v1.
[12] S. Wang, D. S. Utomo, and P. Greening, "Integrating a Mode Choice Model Into Agent-Based Simulation for Freight Transport Planning and Decarbonization Analysis," 2023, doi: 10.1109/wsc60868.2023.10407631.
[13] Q. Wan, X. Zhao, H. Liu, H. Dinçer, and S. Yüksel, "Assessing the new product development process for the industrial decarbonization of sustainable economies," *SAGE Open,* vol. 12, no. 1, p. 21582440211067231, 2022, doi: 10.1177/21582440211067231.
[14] H. Ni, "Towards Decarbonizing the Supply Chain of Dairy Industry: Current Practice and Emerging Strategies," *Carbon Neutrality,* vol. 4, no. 1, 2025, doi: 10.1007/s43979-025-00124-z.
[15] V. Ghisolfi, L. Tavasszy, C. Gonçalo Homem de Almeida, C. Gisele de Lorena Diniz, and G. M. Ribeiro, "Freight Transport Decarbonization: A Systematic Literature Review of System Dynamics Models," *Sustainability,* vol. 14, no. 6, p. 3625, 2022, doi: 10.3390/su14063625.
[16] M. Jafari, A. Botterud, and A. Sakti, "Decarbonizing power systems: A critical review of the role of energy storage," *Renewable and Sustainable Energy Reviews,* vol. 158, p. 112077, 2022, doi: 10.1016/j.rser.2022.112077.
[17] L. Victor-Gallardo, "Economic Evaluation of Decarbonizing the Electricity Sector in the Dominican Republic," *Frontiers in Climate,* vol. 6, 2024, doi: 10.3389/fclim.2024.1380382.
[18] A. Datta, S. Coates, A. Rossiter, and R. Krishnamoorti, "Reskilling and upskilling for decarbonization: analyzing micro-credential programs for energy workforce development," *The Journal of Continuing Higher Education,* vol. 73, no. 1, pp. 64-83, 2025. [Online]. Available: https://doi.org/10.1080/07377363.2024.2377777.
[19] S. Rej, A. Bandyopadhyay, M. Murshed, H. Mahmood, and A. Razzaq, "Pathways to decarbonization in India: The role of environmentally friendly tourism development," *Environmental Science and Pollution Research,* vol. 29, pp. 1-22, 2022, doi: 10.1007/s11356-022-19239-2.