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Examining the Impact of Sustainable Supply Chain Practices on HSE Outcomes in the Alloy Steel Industry Using Structural Equation Modeling

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Abbreviations
- **β:** Standardized path coefficient
- **R²:** Coefficient of determination
- **SRMR:** Standardized Root Mean Square Residual
- **NFI:** Normed Fit Index
- **Q²:** Predictive relevance index

ABSTRACT

Introduction: This study investigates the connection between sustainable supply chain practices and Health, Safety, and Environment (HSE) outcomes in the alloy steel industry using Structural Equation Modeling (SEM).

Materials and Methods: A cross-sectional survey was conducted among 120 industry professionals, selected through purposive, non-random sampling to ensure their expertise in HSE and supply chain management. Data were collected using validated questionnaires measuring four dimensions of sustainable supply chain practices—supplier management, customer relationships, internal processes, and organizational learning—alongside HSE outcomes.

Results: The data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS software, selected for its suitability in modeling complex constructs with moderate sample sizes. The measurement model demonstrated acceptable reliability (Cronbach's alpha > 0.7) and satisfactory convergent and discriminant validity. The findings from the structural model indicated that all four dimensions of sustainable supply chain practices had a significant and positive impact on HSE outcomes (path coefficients = 0.131–0.325, $p < 0.05$), with internal processes showing the strongest influence. The model exhibited high explanatory power ($R^2 = 0.854$).

Conclusion: These findings suggest that aligning sustainable supply chain practices—particularly internal process optimization—with HSE objectives can substantially enhance the sustainable performance of the alloy steel industry. However, the findings should be interpreted with caution due to the cross-sectional design, and depended on self-reported data, and use of purposive, non-random sampling, which may limit causal inference and generalizability.

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Introduction

The pursuit of sustainable development has become a central paradigm in global industrial policies. This shift is driven by stricter environmental regulations, stakeholder pressures, and the recognition that long-term economic viability depends on ecological preservation and social responsibility [1, 2]. Industries are moving

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from profit-centric models to triple-bottom-line approaches (economic, environmental, and social), integrating sustainability into their core operations [3]. In high-risk sectors such as alloy steel production, where processes involve significant environmental impacts and occupational hazards, adopting sustainable practices is essential for competitive survival [4].

The alloy steel industry is critical for industrial infrastructure, providing materials for the construction, automotive, and manufacturing sectors [5]. Its operations are energy-intensive, consume substantial resources, and can cause environmental degradation through emissions, wastewater, and industrial waste [6]. These challenges necessitate robust Health, Safety, and Environment (HSE) management systems to mitigate occupational hazards and reduce ecological footprints [7]. Traditional HSE approaches have focused on compliance. In contrast, modern strategies emphasize proactive and integrated systems aligned with organizational objectives [8].

Supply chain management has also evolved significantly. It is no longer purely logistical but a strategic lever for sustainability [9]. Sustainable supply chain practices coordinate activities from raw material extraction to end-of-life product management to reduce environmental impact. They focus on environmental protection, social equity and economic viability [10]. Practices such as green procurement, ethical sourcing, energy-efficient production, waste reduction, and reverse logistics create closed-loop systems that minimize negative impacts and maximize value creation [11]. Integrating sustainability into supply chains reduces costs, mitigates risks, enhances brand reputation, and improves stakeholder relations [12].

Despite their importance, the connection between sustainable supply chain management and HSE outcomes remains underexplored [13]. Some studies examine supply chain effects on operational performance [14], while others have investigated HSE determinants [15]. Few, however, empirically test the links between specific supply chain dimensions and HSE indicators. This gap is especially pronounced in heavy industries, where synergies could be substantial [16].

Although this study focuses on environmental and safety aspects, worker health—both physical and mental—should not be overlooked. Improvements in sustainability and safety practices can enhance overall well-being by reducing hazards and promoting healthier working environments [17].

The theoretical foundation based on the Natural Resource-Based View (NRBV) and stakeholder theory [18]. NRBV suggests that firms that develop capabilities in pollution prevention and product stewardship can achieve competitive advantages [19]. Stakeholder theory highlights that addressing the concerns of employees, communities, regulators, and customers improves organizational outcomes [20]. In supply chains, sustainable practices reduce risks, improve resource efficiency, and foster continuous improvement [21]. However, the mechanisms through which supplier management, internal processes, customer relations, and organizational learning affect HSE outcomes remain unclear [22]. Grasping these relationships is essential for creating focused interventions. Previous research has often examined these areas separately, limiting managerial decision-making [23].

This study fills these gaps by creating a conceptual model that links sustainable supply chain practices to HSE outcomes in alloy steel. Using Structural Equation Modeling (SEM), this study analyzes how supplier management, internal processes, customer relations, and organizational learning affect HSE efficiency. This study adds to the literature by offering empirical evidence in a high-risk industrial context, identifying key supply chain dimensions, and offering insights for the development of integrated management systems. Iran's alloy steel sector is an appropriate context owing to its economic importance, environmental challenges, and ongoing HSE improvements. Focusing on this industry allows the generation of relevant findings and contributes to broader discussions on sustainability management in industrial settings.

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Materials and Methods

Research Approach and Subjects

This applied, descriptive, cross-sectional investigation was undertaken in the alloy steel sector in Yazd City, Iran. The study population comprised experts, supervisors, and managers directly involved in supply chain management and health, safety, and environmental (HSE) operations. Participants were selected using purposive sampling to ensure that they had sufficient domain-specific expertise. The inclusion criteria for expert selection included at least 5 years of applicable proficiency in the supply chain and HSE areas, as well as an appropriate job position that allowed them to have substantial involvement in supply chain and HSE decision-making.

A total of 120 respondents participated in this study. The sufficiency of the sample size was evaluated based on multiple criteria relevant to Structural Equation Modeling based on the Partial Least Squares approach (PLS-SEM). First, according to the 10-times guidline, the sample size exceeded ten times the maximum number of structural paths directed at any latent construct in the model. Second, a statistical power analysis was conducted in line with the recommendations by Mastana [24] indicating that a minimum sample size of approximately 100 is sufficient to detect medium effect sizes ($f^2 = 0.15$) at a significance level of 0.05 with a statistical power of 0.80 in PLS-SEM models of comparable complexity. Therefore, the final sample size of 120 respondents was considered adequate for robust parameter estimation and hypothesis testing [25].

Measurement Instruments

Data were collected using two validated questionnaires:

Sustainable Supply Chain Practices Questionnaire: Adapted from Zhang et al. [26], this 31-item instrument measures four dimensions assessed using a 5-point Likert scale (1=Strongly Disagree to 5=Strongly Agree):

- Supplier management (8 items)
- Customer relations (7 items)
- Internal sustainable processes (9 items)
- Organizational learning (7 items)

HSE Outcomes Questionnaire: Developed by Sørensen et al. [27], this 21-item scale assesses HSE outcomes across safety compliance, occupational health indicators, and environmental performance metrics using a 5-point Likert scale.

Common Method Bias Assessment

Harman's single-factor test was performed to evaluate common method bias (CMB). The findings show that no single factor explains most of the variance, implying that common method bias is unlikely to significantly affect the results. However, as with all self-reported cross-sectional survey studies, the possibility of common method variance cannot be completely ruled out.

Analytical Approach

The study employed Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS 3.0 to analyze the data. The analysis was conducted in two phases:

1.**Measurement model Evaluation** : This involved assessing reliability (Cronbach's alpha, composite reliability), convergent validity (average variance extracted, factor loadings), and discriminant validity (Fornell-Larcker criterion).

2.**Structural model Evaluation**: The proposed relationships were tested using path coefficients significance levels (via bootstrapping with 5000 samples), and model fit indicators (R^2, Q^2, SRMR).

Results

Descriptive Statistics and Data Screening

Before the main analysis, an initial data screening was carried out to verify data quality and its appropriateness for Structural Equation Modeling. The dataset comprising 120 complete responses showed no missing data. The data met the assumptions for PLS-SEM, with no significant issues detected regarding multivariate normality, skewness, or kurtosis.

Measurement Model Analysis

Reliability and Convergent Validity

The measurement model demonstrated excellent psychometric properties, as summarized in Table

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1. All constructs exceeded the recommended thresholds for reliability, with Cronbach's alpha values ranging from 0.757 to 0.950 and composite reliability values from 0.847 to 0.959, all well above the 0.70 benchmark [10]. Convergent validity was established through Average Variance Extracted (AVE) values, all exceeding the 0.50 threshold, indicating that the constructs explain more than half of the variance in their indicators.

Table 1: Reliability and Convergent Validity Assessment.

Construct	Cronbach's Alpha	Composite Reliability	AVE
HSE Outcomes	0.950	0.959	0.510
Supplier Management	0.846	0.892	0.570
Organizational Learning	0.782	0.863	0.606
Internal Processes	0.894	0.919	0.524
Customer Relations	0.757	0.847	0.520

Factor Loadings and Indicator Reliability

All standardized factor loadings exceeded the recommended value of 0.70, demonstrating adequate reliability. The lowest loading observed was 0.714, and most loadings were above 0.80, indicating strong relationships between the indicators and their respective constructs.

Evaluation of Discriminant Validity
Discriminant validity was evaluated using the Fornell–Larcker criterion. As presented in Table 2, the square root of the average variance extracted (AVE) for each construct was greater than its correlations with the other constructs, thereby indicating satisfactory discriminant validity according to this criterion. Given the conceptual proximity of sustainability-related constructs, these results should be interpreted with theoretical distinctions.

Table 2: Discriminant Validity.(Fornell-Larcker) Approach

Construct	HSE Outcomes	Supplier Mgmt	Org Learning	Internal Processes	Customer Relations
HSE Outcomes	0.714				
Supplier Management	0.709	0.755			
Organizational Learning	0.634	0.667	0.778		
Internal Processes	0.661	0.704	0.709	0.724	
Customer Relations	0.646	0.752	0.770	0.705	0.721

Structural Model Assessment

Collinearity Assessment

Prior to analyzing the structural relationships, the variance inflation factor (VIF) values were evaluated to check for collinearity. All VIF values fell between 1.85 and 2.43, well under the conservative cutoff of 3.3, suggesting that collinearity did not pose a problem in the structural model.

Coefficient of Determination (R^2)

The structural model yielded an R^2 value of 0.854 for the HSE outcomes, indicating a high proportion of explained variance. This high R^2 may reflect the conceptual closeness of sustainable supply chain practices and HSE-related constructs in high-risk industrial environments, where process, safety, and environmental management systems are inherently interrelated.

Effect Sizes (f^2)

Effect sizes (f^2) were computed to evaluate the relative influence of each predictor variable. The findings indicated that internal processes had the strongest effect ($f^2 = 0.185$), followed by customer relations ($f^2 = 0.162$), organizational learning (f^2 =

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0.143), and supplier management (f^2 = 0.045). According to Cohen's guidelines, internal processes, customer relations, and organizational learning showed medium to large effects, while supplier management showed a small effect.

Predictive Relevance (Q^2)

The model's predictive capability was evaluated using the Stone-Geisser Q^2 value obtained through the blindfolding procedure. The Q^2 value for HSE outcomes was 0.391, which is considerably greater than zero, indicating the model possesses strong predictive relevance.

Hypothesis Testing Results

The path coefficients and hypothesis-testing results are presented in Table 3. All four hypotheses were supported at significance levels of $p < 0.05$ or better. To assess path significance, a bootstrapping approach with 5,000 subsamples was conducted.

Table 3: Hypothesis Testing Results.

Hypothesis	Relationship	Path Coefficient	t-value	p-value	95% Confidence Interval
H1	Supplier Management → HSE Outcomes	0.131	2.595	0.011	[0.031, 0.231]
H2	Organizational Learning → HSE Outcomes	0.255	3.285	0.001	[0.102, 0.408]
H3	Internal Processes → HSE Outcomes	0.325	4.189	0.000	[0.174, 0.476]
H4	Customer Relations → HSE Outcomes	0.305	2.729	0.007	[0.083, 0.527]

Specific Path Analysis

- **H1**: Supplier management showed a positive and significant effect on HSE outcomes (β = 0.131, $p < 0.05$), although this was the weakest relationship among the four dimensions.
- **H2**: Organizational learning has a strong positive effect (β = 0.255, $p < 0.001$), indicating its importance in enhancing HSE performance.
- **H3**: Internal sustainable processes exhibited the strongest effect (β = 0.325, $p < 0.001$), highlighting the critical role of internal operational excellence in achieving sustainability.
- **H4**: Customer relations showed a substantial positive influence (β = 0.305, $p < 0.01$), emphasizing the significance of external stakeholder relationships.

Figure 1 illustrates the structural equation model developed to test the hypothesized relationships between sustainable supply chain practices and HSE outcomes. The model was evaluated using Partial Least Squares Structural Equation Modeling (PLS-SEM) in SmartPLS 3.0 software. All path coefficients shown are standardized estimates, meaning they are on a comparable scale and allow for direct comparisons between different paths in the model. Significance levels were determined using bootstrapping with 5000 subsamples to ensure robust and reliable results. Bootstrapping was performed to assess the stability of the estimates and calculate confidence intervals for the path coefficients, which further reinforced the validity of the model.

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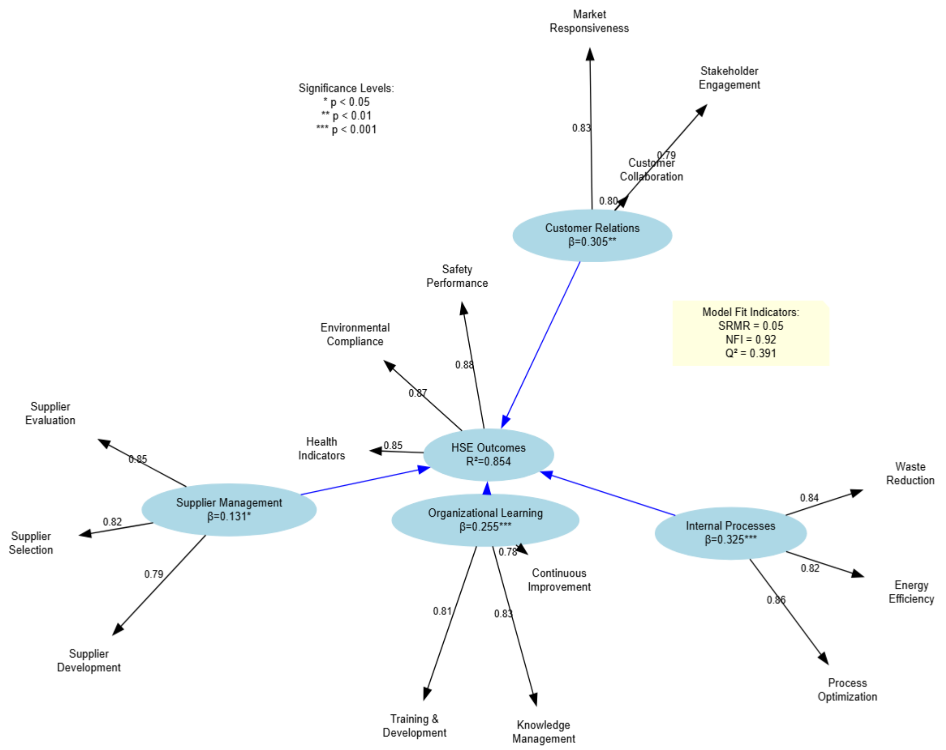

Figure 1: Structural Equation Modeling (SEM) Results of Sustainable Supply Chain Practices and HSE Outcomes Relationships.

As shown in Figure 1, the structural model revealed significant positive relationships between all four sustainable supply chain practice dimensions and HSE outcomes. Internal sustainable processes demonstrated the strongest effect ($\beta = 0.325$, $p < 0.001$), followed by customer relations ($\beta = 0.305$, $p < 0.01$), organizational learning ($\beta = 0.255$, $p < 0.001$), and supplier management ($\beta = 0.131$, $p < 0.05$). The measurement model showed strong psychometric properties, with all factor loadings exceeding 0.70.

Model Fit Indices

The overall fit of the model was evaluated using various fit indices. The Standardized Root Mean Square Residual (SRMR) was 0.05, which is below the recommended threshold of 0.08, indicating a strong model fit according to current PLS-SEM standards. The Normed Fit Index (NFI) was 0.92, surpassing the widely accepted threshold of 0.90, thereby confirming the model's validity. Furthermore, the model demonstrated a good approximate fit, as reflected by the RMS_theta value of 0.12, which is deemed acceptable for PLS-SEM models according to recent methodological recommendations.

Discussion

This study offers strong empirical evidence that sustainable supply chain practices (SSCP) significantly enhance HSE outcomes in the alloy steel sector. These outcomes support and build upon existing literature on the synergistic benefits of integrating sustainability principles into supply chain operations while addressing critical gaps in the literature regarding specific mechanistic pathways [15, 28]. The strongest relationship was observed between internal sustainable processes and HSE outcomes ($\beta = 0.325$, $p < 0.001$), indicating that optimizing internal operations for sustainability inherently creates safer and more controlled work environments [29].The implementation of waste minimization protocols, energy efficiency measures, and process standardization not only reduces environmental impacts but also eliminates workplace hazards at their source [30, 31].

The significant effect of organizational learning

($\beta = 0.255$, $p < 0.001$) highlights the critical role of knowledge management systems and safety culture in mediating the relationship between sustainability initiatives and HSE outcomes [32, 33].Customer relations also emerged as a significant factor ($\beta = 0.305$, $p < 0.01$), reflecting the growing influence of market mechanisms and stakeholder pressure on HSE performance [34-36]. Supplier management, while demonstrating the smallest effect size ($\beta = 0.131$, $p < 0.05$), still affirmed the importance of supply chain integration for HSE outcomes, emphasizing that HSE risks extend beyond organizational boundaries [37]. The high explanatory power of the model ($R^2 = 0.854$) indicates that SSCP collectively account for the majority of the variance in HSE outcomes [38, 39]. From a theoretical perspective, the findings validate the links between SSCM and HSE, extend the Natural Resource-Based View, and support stakeholder theory by quantifying how external pressures translate into improved HSE outcomes [40].

The results offer several clear, industry-specific recommendations for managers and practitioners in the alloy-steel sector. First, managers should prioritize the integration of HSE objectives into core internal processes, such as production planning, equipment maintenance, and process control. Investments in internal sustainability initiatives, including energy-efficient technologies, waste minimization programs, and standardized operating procedures, serve as dual-purpose strategies that enhance environmental performance while simultaneously reducing workplace hazards [41, 42].

Second, the adoption of advanced process technologies and automation can improve energy efficiency and reduce manual intervention in high-risk operations, directly enhancing safety outcomes. For instance, implementing closed-loop water systems can conserve resources while limiting worker exposure to hazardous effluents [43]. Third, cultivating organizational learning mechanisms, such as near-miss reporting systems, cross-functional safety committees, and digital platforms for sharing best practices, strengthens hazard identification, preventive action implementation, and adaptive risk responses [44].

Fourth, customer engagement and stakeholder management should be leveraged as tools to drive HSE improvements. Alloy steel companies serving automotive or construction clients may experience pressure to comply with sustainability standards (e.g., ISO 14001 and ISO 45001), which incentivizes investment in HSE infrastructure [45, 46]. Finally, firms should consider supplier development programs and joint risk assessments to ensure that HSE standards are maintained across the supply chain, as supplier incidents can disrupt operations and affect organizational reputation [47, 48].

Despite these contributions, this study has several limitations. First, sampling constraints arise from the purposive, non-random sampling method used, which could restrict the broader applicability of the results beyond Iran's alloy steel sector. Second, the study relied on self-reported questionnaire data, which introduced potential bias and may have inflated the observed relationships between SSCP and HSE outcomes. Third, the cross-sectional study design restricts the capacity to determine causal connections between sustainable practices and HSE performance.

Subsequent research needs to address these limitations by employing longitudinal designs to assess causality, using objective HSE performance indicators to reduce self-report bias, and applying probability-based sampling across diverse industries and geographical locations. Additionally, more stringent approaches to assessing discriminant validity (e.g., the HTMT ratio) and multi-source data collection are recommended to strengthen construct validity.

Conclusion

From a theoretical perspective, this study adds to the literature by empirically confirming the link between sustainable supply chain practices and HSE outcomes, utilizing a well-established PLS-SEM methodology suited for exploratory analysis. It extends the Natural Resource-Based View by demonstrating how sustainable capabilities simultaneously enhance safety and environmental performance.

Practically, the findings provide managers in the

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alloy steel industry with a validated framework for improving HSE outcomes through targeted supply chain interventions. The strong effect of internal processes suggests that organizations should prioritize operational optimization and waste reduction initiatives. Moreover, investments in employee training, customer collaboration, and supplier development can yield significant HSE improvements.

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Conflicts of Interest

None declared.

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Ethical Considerations

This study was conducted in accordance with the ethical standards of the ACECR Research Ethics Committee. Informed consent was obtained from all participants, and confidentiality of data was maintained throughout the research.

Code of Ethics

Approved by the ACECR Research Ethics Committee (IR.ACECR.JDM.REC.1401.047).

Authors' Contributions

All authors contributed to drafting and revising the manuscript and approved the final version. Rohollah Fallah Madvari: Conceptualization, methodology, analysis, writing, Abolfazl Kamel Rastegar Qavi: Data collection, literature review, editing, Ali Sadri Esfahani & Afarin Akhavan: Statistical analysis, supervision and Sepideh Kamali: Project administration, funding, validation.

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