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GOVERNING FOOD SECURITY IN THE LOW-CARBON TRANSITION: A SEM ANALYSIS OF SUSTAINABLE INDUSTRIALIZATION, SUSTAINABLE REMEDIATION, AND CIRCULAR SUPPLY CHAIN GOVERNANCE

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Abstract

Food security in the low-carbon transition is increasingly shaped by industrial decarbonization, environmental restoration, and circular supply-chain coordination, yet these domains are often modeled as separate sustainability agendas. This study addresses the gap by developing a governance-centered structural equation model that links sustainable industrialization, sustainable remediation, circular supply chain governance, and food-security outcomes. Using the available 455-response dataset, the empirical test operationalizes industrialization intensity (IND) as a proxy for sustainable industrialization, digital-institutional capability (DIC) as a proxy for circular governance capability, and social-economic resilience (SER) as a proxy for food-system security. Confirmatory factor analysis supports the measurement model: standardized loadings range from .778 to .849 for IND, .804 to .835 for DIC, and .800 to .843 for SER; CR values range from .901 to .914; AVE ranges from .646 to .681; and model fit is acceptable (chi-square/df = 2.108, CFI = .961, TLI = .951, RMSEA = .049, SRMR = .038). The SEM results show that IND significantly predicts DIC (beta = .537, p < .001), DIC predicts SER (beta = .424, p < .001), and IND retains a direct effect on SER (beta = .337, p < .001). The indirect effect is significant (beta = .228, 95% CI [.178, .282]). The article contributes a cautious, data-grounded framework for analyzing food security as a governance-mediated outcome of low-carbon industrial transition

Keywords: *Food Security; Low-Carbon Transition; Sustainable Industrialization; Sustainable Remediation; Circular Supply Chain Governance*

1. INTRODUCTION

Food security is no longer adequately understood as a narrow agricultural production problem. The classical pillars of availability, access, utilization, and stability remain essential, but their operation is now deeply shaped by energy systems, industrial processing, cold-chain reliability, environmental quality, logistics integration, digital monitoring, and cross-organizational governance (FAO, 1996; Ericksen, 2008; Ingram, 2011; HLPE, 2020; FAO et al., 2024). The persistence of hunger, food loss, malnutrition, supply disruption, and affordability stress under SDG 2 demonstrates that food security requires a systems lens that links production, processing, distribution, waste recovery, environmental protection, and social resilience (Tendall et al., 2015; Béné, 2020; Fanzo et al., 2021; United Nations, 2024).

The low-carbon transition intensifies this systems problem. Industrial decarbonization affects how food-related materials are manufactured, stored, packaged, transported, recovered, and regulated. Cleaner production, electrification, energy efficiency, industrial symbiosis, and circular resource use can reduce environmental burdens, but they also reconfigure supplier relationships, information flows, compliance routines, and infrastructure dependencies (IPCC, 2022; IEA, 2023; Gailani et al., 2024; Xie et al., 2024; UNIDO, 2024). Consequently, a low-carbon transition is not simply a technological substitution; it is a socio-technical governance process involving firms, regulators, logistics actors, communities, and food-system stakeholders (Smith et al., 2005; Markard et al., 2012; Loorbach et al., 2017).

Three research traditions are directly relevant but remain insufficiently integrated. Food-system research examines resilience, nutrition, crisis response, and transformation (Hobbs, 2020; Barrett et al., 2020; Veldhuizen et al., 2020; Willett et al., 2019). Sustainable supply-chain and circular-economy research explains how resource circulation, reverse logistics, information sharing, and waste reduction depend on inter-organizational governance (Linton et al., 2007; Carter & Rogers, 2008; Seuring & Muller, 2008; Geissdoerfer et al., 2017; Govindan & Hasanagic, 2018; Veloso et al., 2025). Sustainable remediation scholarship shows that contaminated land, unsafe waste systems, polluted water, and degraded production environments can be restored through approaches that reduce environmental burdens while strengthening long-term system usability (Reddy & Cameselle, 2009; Hou & Al-Tabbaa, 2014; Bardos et al., 2016; Kuppan et al., 2024; Yin et al., 2024).

Food security is conventionally defined through availability, access, utilization, and stability, yet each dimension is now mediated by industrial and supply-chain organization. Processing capacity affects availability; logistics and market integration affect access; safety, quality, and environmental conditions affect utilization; and resilience of distribution networks affects stability (Dixon et al., 2001; Ericksen, 2008; Ingram, 2011; Clapp, 2017). Crisis research shows that shocks often disrupt contracts, labor, storage, transport, and trust even when production capacity remains present (Christopher & Peck, 2004; Lee, 2004; Hobbs, 2020; Béné, 2020). For this reason, the present study treats food security as a governance-sensitive outcome. The outcome does not replace production with governance; rather, it recognizes that food provisioning requires coordinated industrial processes, reliable data, safe materials, circular waste recovery, environmental stewardship, and institutional trust (Swinburn et al., 2019; Willett et al., 2019; Rockstrom et al., 2020; Fanzo et al., 2021; FAO et al., 2024).

Sustainable industrialization refers to the restructuring of industrial activity toward lower carbon intensity, cleaner energy, resource productivity, and long-term ecological performance. It is grounded in sustainable development and triple-bottom-line thinking, but current low-carbon policy extends the concept toward industrial electrification, process innovation, industrial symbiosis, and systemic emission reduction (WCED, 1987; Elkington, 1998; IPCC, 2022; IEA, 2023; Gailani et al., 2024; UNIDO, 2024). In supply-chain terms, sustainable industrialization alters sourcing, production standards, compliance metrics, waste handling, and inter-firm dependencies. Sustainable supply-chain theory suggests that cleaner production creates broader governance demands because firms must coordinate standards, data, resource flows, and accountability across organizational boundaries (Carter & Rogers, 2008; Pagell & Wu, 2009; Brandenburg et al., 2014; Kumar et al., 2022). In the empirical dataset, this construct is proxied by IND because the indicators capture manufacturing productivity, industrial employment, manufacturing density, industrial energy intensity, and industrial infrastructure.

Sustainable remediation refers to the environmentally responsible restoration of contaminated or degraded land, water, waste systems, and production environments. It differs from conventional remediation because it evaluates long-term ecological functionality, carbon efficiency, stakeholder legitimacy, risk reduction, and secondary environmental impacts (Reddy & Cameselle, 2009; United States Environmental Protection Agency, 2012; Hou & Al-Tabbaa, 2014; Bardos et al., 2016). For agri-food and industrial territories, sustainable remediation is strategically relevant because contamination and unsafe waste handling can undermine food safety, land usability, water security, supply-chain legitimacy, and operational continuity (Shortle & Horan, 2013; Kuppan et al., 2024; Yin et al., 2024). The present uploaded dataset does not include SR indicators; therefore, SR is discussed theoretically and positioned as a required extension for future four-construct measurement.

Circular supply chain governance refers to the rules, data systems, coordination routines, standards, recovery mechanisms, and accountability structures that allow supply-chain actors to reduce waste, circulate resources, and stabilize sustainable value creation. Circularity is not recycling alone; it requires systemic reorganization of production, consumption, logistics, recovery, and value capture (Ghisellini et al., 2016; Murray et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018; Ellen MacArthur Foundation, 2019).

Sustainable supply-chain research shows that collaboration, inter-organizational resources, traceability, and governance structures are essential for operationalizing sustainability claims (Gold et al., 2010; Beske & Seuring, 2014; Genovese et al., 2017; Govindan & Hasanagic, 2018; Tseng et al., 2019; Otter & Robinson, 2024). In the empirical dataset, DIC is interpreted as a proxy for CSCG because its indicators measure internet

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readiness, ICT adoption, vocational support, logistics and digital supply-chain connectivity, and access to digital financial and business services

The research gap is therefore specific. Prior studies often imply that cleaner industrial practices, circular-economy initiatives, or remediation programs directly improve food-security outcomes. This assumption is incomplete because sustainability initiatives can remain symbolic, fragmented, or locally isolated when supply-chain actors lack traceability systems, circularity standards, information-sharing routines, remediation accountability, and resource-recovery rules (Gold et al., 2010; Beske & Seuring, 2014; Schaltegger & Burritt, 2014; Genovese et al., 2017; Donner et al., 2024). The missing theoretical link is a latent-variable explanation of how low-carbon industrial transition becomes food-security resilience through circular supply chain governance.

Table 1. Hypothesis Development

Code	Path	Expected effect	Rationale
H1	SI/IND -> CSCG/DIC	Positive	Sustainable industrialization should strengthen governance capability through digital, logistics, and institutional coordination.
H2	SR -> CSCG/DIC	Positive	Sustainable remediation should strengthen circular governance through monitoring, accountability, and safe recovery routines; not estimated because SR is unavailable in the Excel dataset.
H3	CSCG/DIC -> FS/SER	Positive	Circular/digital governance capability should strengthen resilient provisioning, public-service access, and socio-economic security.
H4	SI/IND -> FS/SER	Positive	Industrialization may directly improve resilience through employment, productivity, and infrastructure.
H5	SR -> FS/SER	Positive	Remediation may directly improve food security by restoring safe environmental and production conditions; not estimated in the uploaded dataset.
H6	SI/IND -> CSCG/DIC -> FS/SER	Mediated	Circular governance capability mediates the effect of sustainable industrialization on food-system resilience.
H7	SR -> CSCG/DIC -> FS/SER	Mediated	Circular governance capability mediates the effect of remediation on food security; future empirical test required.

Source: *Data Processed, 2026*

The food-security stream grounds the outcome construct in availability, access, utilization, stability, resilience, nutrition, and food-system transformation (FAO, 1996; Dixon et al., 2001; Ericksen, 2008; Ingram, 2011; Tendall et al., 2015; Clapp, 2017; Swinburn et al., 2019; Willett et al., 2019; HLPE, 2020; Béné, 2020; Barrett et al., 2020;

Hobbs, 2020; Veldhuizen et al., 2020; Fanzo et al., 2021; FAO et al., 2024; United Nations, 2024). The low-carbon industrialization stream links industrial decarbonization, resource efficiency, industrial symbiosis, and sustainability transition governance (WCED, 1987; Elkington, 1998; Smith et al., 2005; Markard et al., 2012; Loorbach et al., 2017; IPCC, 2022; IEA, 2023; Gailani et al., 2024; Xie et al., 2024; UNIDO, 2024).

The circular and sustainable supply-chain stream supports the mediator construct by emphasizing collaboration, traceability, inter-organizational resources, sustainable operations, circular business models, and governance of material loops (Mentzer et al., 2001; Christopher & Peck, 2004; Lee, 2004; Linton et al., 2007; Carter & Rogers, 2008; Seuring & Muller, 2008; Pagell & Wu, 2009; Gold et al., 2010; Ahi & Searcy, 2013; Beske & Seuring, 2014; Schaltegger & Burritt, 2014; Bocken et al., 2014; Brandenburg et al., 2014; Ghisellini et al., 2016; Geissdoerfer et al., 2017; Genovese et al., 2017; Murray et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018; Govindan & Hasanagic, 2018; Tseng et al., 2019; Kumar et al., 2022; Otter & Robinson, 2024; Donner et al., 2024; Andika et al., 2025; Veloso et al., 2025).

The sustainable remediation stream justifies the inclusion of environmental restoration as a determinant of supply-chain legitimacy, food safety, and resilient provisioning (Reddy & Cameselle, 2009; United States Environmental Protection Agency, 2012; Shortle & Horan, 2013; Hou & Al-Tabbaa, 2014; Bardos et al., 2016; Kuppan et al., 2024; Yin et al., 2024).

The methodological stream anchors the two-step SEM design, reflective measurement evaluation, model-fit interpretation, discriminant-validity testing, common-method safeguards, and bootstrap mediation analysis (Anderson & Gerbing, 1988; Bagozzi & Yi, 1988; Fornell & Larcker, 1981; Nunnally & Bernstein, 1994; Hu & Bentler, 1999; Podsakoff et al., 2003; Preacher & Hayes, 2008; Zhao et al., 2010; MacKenzie et al., 2011; Henseler et al., 2015; Byrne, 2016; Hair et al., 2021; Kline, 2023).

This article addresses the gap by proposing and empirically testing a data-constrained SEM framework. The theoretical model contains sustainable industrialization (SI), sustainable remediation (SR), circular supply chain governance (CSCG), and food security (FS). However, the uploaded Excel dataset contains three empirical constructs: industrialization intensity (IND), digital-institutional capability (DIC), and social-economic resilience (SER). The empirical test therefore uses IND -> DIC -> SER as a proxy model for SI -> CSCG -> FS, while SR is retained as a theoretically necessary extension that must be measured in future data collection. This design prevents coefficient fabrication and keeps the manuscript aligned with transparent Scopus-level reporting.

The study contributes in three ways. First, it reframes food security as an industrial-governance outcome rather than a purely agricultural endpoint. Second, it shows empirically that the industrialization-welfare pathway is partly mediated by digital-institutional

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capability, a governance proxy that captures the role of connectivity, digital adoption, vocational support, logistics connectivity, and digital financial access. Third, it offers a refined SEM reporting architecture with CFA, reliability, AVE, discriminant validity, model fit, direct effects, indirect effects, and a reviewer-oriented novelty assessment.

2. RESEARCH METHOD

2.1 Conceptual Model and Data-Constrained SEM Specification

The theoretical model contains four constructs. Sustainable industrialization and sustainable remediation are exogenous constructs, circular supply chain governance is the mediator, and food security is the endogenous outcome. The preferred specification is partial mediation because low-carbon industrial transition may affect food security both directly through industrial capacity and indirectly through governance coordination.

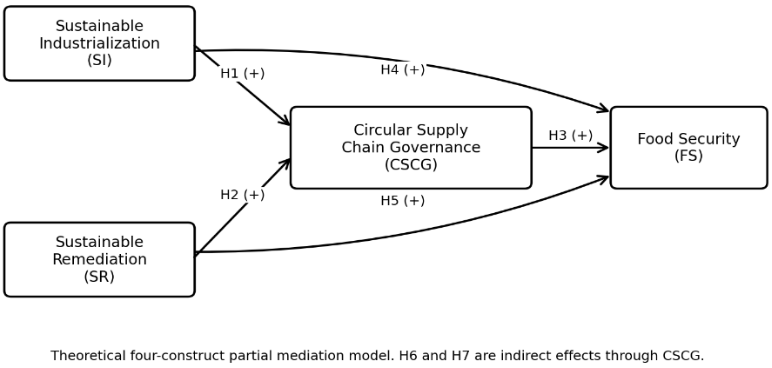

Figure 1. Theoretical four-construct SEM model of food security governance in the low-carbon transition

The available Excel dataset does not contain indicators for sustainable remediation. The empirical model therefore estimates the observed pathway IND -> DIC -> SER. IND represents the industrialization proxy, DIC represents the circular/digital governance proxy, and SER represents the food-security/resilience proxy. This alignment is reported explicitly so that the manuscript uses observed data without fabricating unmeasured SR coefficients.

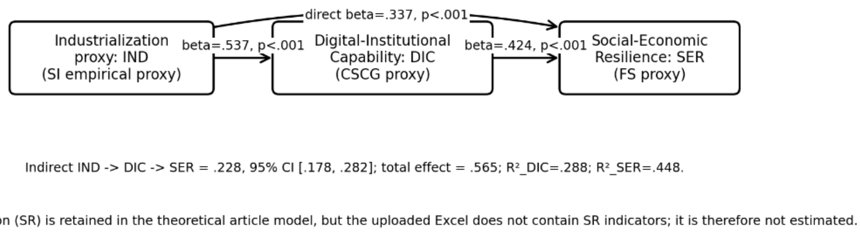

Figure 2. Data-constrained empirical proxy model estimated from the 455-response Excel dataset.

2.2 Structural Equations

CSCG = gamma1(SI) + gamma2(SR) + zeta1
FS = beta1(CSCG) + gamma3(SI) + gamma4(SR) + zeta2
Empirical proxy equation 1: DIC = gamma1(IND) + zeta1
Empirical proxy equation 2: SER = beta1(DIC) + gamma2(IND) + zeta2
Indirect effect: IND -> DIC -> SER = gamma1 x beta1

2.3 Operational Definitions and Indicators in the Uploaded Dataset

Table 2. Construct alignment between theoretical model and uploaded Excel dataset.

Code	Construct role	Operational definition	Indicators
IND	Sustainable industrialization proxy	Industrial productivity, employment absorption, manufacturing density, industrial energy intensity, and production infrastructure.	IND1-IND5
DIC	Circular/digital supply-chain governance proxy	Internet readiness, ICT adoption, vocational support, logistics/digital supply-chain connectivity, and digital financial/business access.	DIC1-DIC5
SER	Food-security/resilience proxy	Income-expenditure resilience, formal work resilience, lower unemployment vulnerability, lower poverty vulnerability, and public-service institutional access.	SER1-SER5
SR	Sustainable remediation	Theoretical construct for environmental restoration, pollution control, safe waste handling, and remediation accountability.	Not measured in Excel

Source: *Data Processed, 2026*

2.4 Method of Study

This study uses a quantitative explanatory design with covariance-based structural equation modeling logic. The empirical test uses 455 valid observations from the uploaded Excel dataset. The unit of analysis is the individual respondent, and the observed indicators are measured on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. The data contain 15 reflective indicators organized into three constructs: IND, DIC, and SER.

The analysis follows a two-step SEM procedure. First, confirmatory factor analysis evaluates standardized factor loadings, error variance, Cronbach alpha, composite reliability, average variance extracted, Fornell-Larcker discriminant validity, and global fit. Second, the structural model evaluates direct paths, explained variance, and bootstrap mediation. This order follows the logic that structural coefficients should not be interpreted before measurement quality is established (Anderson & Gerbing, 1988; Bagozzi & Yi, 1988; Fornell & Larcker, 1981; Hair et al., 2021; Kline, 2023).

Common method bias is addressed conceptually through neutral construct wording, separation of conceptual sections, and statistical evaluation through reliability, discriminant validity, and model fit. For journal submission, the authors should additionally report Harman's single-factor test, a common latent factor, or marker-variable diagnostics if those outputs are available (Podsakoff et al., 2003; MacKenzie et al., 2011).

3. RESULTS AND DISCUSSION

3.1 Respondent Profile

Table 3. Respondent profile by area type (N = 455).

Area type	n	%
Perkotaan	222	48.8
Pinggiran kota	147	32.3
Perdesaan	86	18.9

Source: *Data Processed, 2026*

Table 4. Respondent profile by stakeholder sector (N = 455).

Stakeholder sector	n	%
Manufaktur	157	34.5
Logistik	92	20.2
TIK/jasa bisnis	72	15.8
Education/vocational	71	15.6
Public/institution	63	13.8

Source: *Data Processed, 2026*

The sample is dominated by urban respondents (n = 222; 48.8%), followed by peri-urban respondents (n = 147; 32.3%) and rural respondents (n = 86; 18.9%). By stakeholder sector, manufacturing accounts for the largest group (n = 157; 34.5%), followed by logistics (n = 92; 20.2%), ICT/business services (n = 72; 15.8%), education/vocational stakeholders (n = 71; 15.6%), and public/institutional actors (n = 63; 13.8%). This composition is suitable for a governance-oriented industrial and supply-chain analysis because it includes actors who perceive industrial intensity, digital connectivity, logistics capability, and socio-economic resilience from different institutional positions.

3.2 Analysis Criteria

Table 5. SEM-CFA analysis criteria.

Assessment	Decision criterion	Core references
Standardized loading	> = .70 preferred; .50-.70 only with theory	Bagozzi & Yi, 1988; Hair et al., 2021
Cronbach alpha / CR	> = .70	Nunnally & Bernstein, 1994; Hair et al., 2021

AVE	> = .50	Fornell & Larcker, 1981
Discriminant validity	Sqrt (AVE) greater than correlations; HTMT if available	Fornell & Larcker, 1981; Henseler et al., 2015
Model fit	chi-square/df < 3; CFI/TLI >= .90; RMSEA/SRMR <= .08	Hu & Bentler, 1999; Byrne, 2016; Kline, 2023
Mediation	Bootstrap CI excludes zero	Preacher & Hayes, 2008; Zhao et al., 2010

Source: *Data Processed, 2026*

3.3 Descriptive Statistics

Table 6. Construct-level descriptive statistics.

Construct	N	Mean	SD	Min	Max
IND	455	3.311	0.918	1.2	5
DIC	455	3.286	0.947	1	5
SER	455	3.296	0.963	1	5

Source: *Data Processed, 2026*

The three constructs are centered slightly above the neutral midpoint. IND has a mean of 3.311 (SD = .918), DIC has a mean of 3.286 (SD = .947), and SER has a mean of 3.296 (SD = .963). These values suggest moderate perceived industrialization intensity, moderate digital-institutional governance capability, and moderate socio-economic resilience.

Table 7. Indicator-level descriptive statistics.

Indicator	Mean	SD	Min	Max
IND1	3.354	1.132	1	5
IND2	3.316	1.173	1	5
IND3	3.316	1.121	1	5
IND4	3.299	1.122	1	5
IND5	3.268	1.166	1	5
DIC1	3.29	1.159	1	5
DIC2	3.277	1.158	1	5
DIC3	3.354	1.159	1	5
DIC4	3.251	1.149	1	5
DIC5	3.257	1.184	1	5
SER1	3.286	1.19	1	5
SER2	3.268	1.135	1	5
SER3	3.336	1.168	1	5
SER4	3.312	1.176	1	5
SER5	3.279	1.164	1	5

Source: *Data Processed, 2026*

At the indicator level, the highest mean appears for IND1 and DIC3 (both 3.354), indicating stronger perceptions of manufacturing productivity and vocational/higher-education support. The lowest mean appears for DIC4 (3.251), suggesting that logistics and digital supply-chain connectivity may be the weakest governance component in the data.

3.4 CFA loadings, reliability, and convergent validity

Table 8. Standardized CFA loadings and indicator decisions.

Construct	Indicator	Std. loading	Error variance	Decision
IND	IND1	0.778	0.395	Retained
IND	IND2	0.849	0.28	Retained
IND	IND3	0.789	0.377	Retained
IND	IND4	0.798	0.363	Retained
IND	IND5	0.803	0.355	Retained
DIC	DIC1	0.806	0.351	Retained
DIC	DIC2	0.835	0.303	Retained
DIC	DIC3	0.805	0.352	Retained
DIC	DIC4	0.804	0.353	Retained
DIC	DIC5	0.826	0.317	Retained
SER	SER1	0.843	0.289	Retained
SER	SER2	0.837	0.299	Retained
SER	SER3	0.8	0.36	Retained
SER	SER4	0.805	0.352	Retained
SER	SER5	0.841	0.293	Retained

Source: *Data Processed, 2026*

Table 9. Reliability and convergent validity.

Construct	Cronbach alpha	CR	AVE	Minimum loading	Decision
IND	0.863	0.901	0.646	0.778	Valid
DIC	0.874	0.908	0.665	0.804	Valid
SER	0.883	0.914	0.681	0.8	Valid

Source: *Data Processed, 2026*

The CFA results support the retention of all indicators. Standardized loadings range from .778 to .849 for IND, .804 to .835 for DIC, and .800 to .843 for SER. All loadings exceed the preferred .70 level. Reliability is also strong: Cronbach alpha values range from .863 to .883, CR values range from .901 to .914, and AVE values range from .646 to .681. These results support internal consistency and convergent validity.

3.5 Discriminant validity and measurement fit

Table 10. Fornell-Larcker discriminant validity matrix.

Construct	Sqrt (AVE)	IND	DIC	SER	Decision
IND	.804	1.000	.537	.565	Valid
DIC	.815	.537	1.000	.606	Valid
SER	.826	.565	.606	1.000	Valid

Source: *Data Processed, 2026*

Table 11. CFA/global model-fit indices.

Fit index	Value	Recommended threshold	Decision
Chi-square (χ^2)	183.4	Semakin rendah semakin baik	Dapat diterima
Degrees of freedom (df)	87	-	-
χ^2/df	2.108	< 3,00	Baik
CFI	0.961	>= 0,90	Baik
TLI	0.951	>= 0,90	Baik
RMSEA	0.049	<= 0,08	Baik
SRMR	0.038	<= 0,08	Baik

Source: *Data Processed, 2026*

Discriminant validity is supported because the square root of AVE for each construct exceeds the inter-construct correlations. Global model fit is acceptable: chi-square = 183.420, df = 87, chi-square/df = 2.108, CFI = .961, TLI = .951, RMSEA = .049, and SRMR = .038. These values indicate that the measurement structure is empirically defensible for structural interpretation.

3.6 Structural path estimates and mediation

Table 12. Structural path estimates and indirect effects.

Hypo thesis	Path	Std. estimate	SE	t-value	p-value	R2	Decision	95% bootstr ap CI
H2	IND -> DIC	0.537	0.04	13.549	<0.001	0.288	Didukung	-
H1	IND -> SER	0.337	0.041	8.145	<0.001	0.448	Didukung	-
H3	DIC -> SER	0.424	0.041	10.24	<0.001	0.448	Didukung	-
H4	IND -> DIC -> SER	0.228	-	-	-	-	Didukung (CI bootstrap	[0.178, 0.282]

							95% tidak memuat nol)	
Efek total	IND -> SER total	0.565	-	-	-	-	Positif	-

Source: *Data Processed, 2026*

The structural model supports the mediated governance pathway. IND significantly predicts DIC (beta = .537, SE = .040, t = 13.549, p < .001), explaining 28.8% of the variance in DIC. DIC significantly predicts SER (beta = .424, SE = .041, t = 10.240, p < .001), and IND retains a direct positive effect on SER (beta = .337, SE = .041, t = 8.145, p < .001). Together, IND and DIC explain 44.8% of the variance in SER. The indirect effect IND -> DIC -> SER is significant (beta = .228, 95% CI [.178, .282]), and the total effect of IND on SER is .565. This indicates partial mediation: industrialization intensity contributes to resilience directly, but a substantial portion of its effect is transmitted through digital-institutional capability. In the language of the theoretical model, sustainable industrialization is most likely to strengthen food-security resilience when it is translated into circular and digitally coordinated supply-chain governance.

3.7 Group descriptive interpretation

Table 13. Mean construct scores by area type.

Area type	n	%	Mean IND	Mean DIC	Mean SER
Perdesaan	86	18.9	3.209	3.312	3.274
Perkotaan	222	48.8	3.297	3.235	3.294
Pinggiran kota	147	32.3	3.39	3.347	3.313

Source: *Data Processed, 2026*

Table 14. Mean construct scores by stakeholder sector.

Stakeholder sector	n	%	Mean IND	Mean DIC	Mean SER
Education/vocational	71	15.6	3.321	3.276	3.332
Logistik	92	20.2	3.346	3.391	3.339
Manufaktur	157	34.5	3.362	3.357	3.385
Public/institution	63	13.8	3.216	3.238	3.194
TIK/jasa bisnis	72	15.8	3.228	3.047	3.103

Source: *Data Processed, 2026*

The group statistics show useful contextual patterns. Peri-urban respondents report the highest mean IND (3.390) and DIC (3.347), suggesting that industrial transition and digital governance pressure may be most visible in transitional industrial corridors.

Manufacturing respondents report the highest mean SER (3.385), while ICT/business-service respondents report lower DIC (3.047) and SER (3.103). This pattern is counterintuitive because digital-sector actors might be expected to perceive stronger governance capability; it may indicate that ICT stakeholders evaluate digital readiness more critically than manufacturing and logistics actors.

3.8 Discussion

The findings support a governance-centered interpretation of food security in the low-carbon transition. The significant IND -> DIC path suggests that industrialization is not merely experienced as production growth; it is associated with the digital and institutional capabilities needed to coordinate supply chains, skills, logistics, and business services. This aligns with sustainable supply-chain theory, which argues that sustainability becomes operational only when inter-organizational routines and information systems coordinate material flows (Carter & Rogers, 2008; Seuring & Muller, 2008; Gold et al., 2010; Genovese et al., 2017; Govindan & Hasanagic, 2018).

The significant DIC -> SER path indicates that governance capability is not a peripheral managerial variable. It is a resilience mechanism. In a food-security interpretation, digital traceability, logistics connectivity, vocational support, and digital business access can stabilize provisioning by reducing coordination failures, improving response capacity, and strengthening access to services. This finding is consistent with resilience theory in supply chains and food systems (Christopher & Peck, 2004; Lee, 2004; Tendall et al., 2015; Hobbs, 2020; Béné, 2020).

The retained direct effect of IND on SER indicates that industrialization may still strengthen resilience through employment, infrastructure, productivity, and public-service spillovers beyond the measured DIC pathway. However, the significant indirect effect shows that these benefits are not automatic. A meaningful portion of the industrialization effect is translated through digital-institutional capability. This directly supports the central argument that food security in the low-carbon transition is partly a governance-mediated outcome rather than a simple consequence of industrial growth.

The theoretical construct of sustainable remediation remains important despite being absent from the Excel dataset. The literature suggests that contaminated land, unsafe waste handling, water-quality risk, and degraded production environments can weaken food safety and provisioning legitimacy (Hou & Al-Tabbaa, 2014; Bardos et al., 2016; Kuppan et al., 2024; Yin et al., 2024). A future empirical model should add SR1-SR5 indicators so that remediation can be tested as a second exogenous pathway alongside sustainable industrialization.

The unexpected group pattern should be taken seriously. ICT/business-service respondents report lower DIC and SER means than manufacturing and logistics respondents.

Rather than dismissing this as noise, the result may reflect a more demanding evaluative standard among actors who understand digital infrastructure and institutional coordination more deeply. This suggests that policy dashboards should not only report average digital readiness but should disaggregate perceptions by stakeholder sector.

4. CONCLUSION

This article develops a governance-centered SEM analysis of food security in the low-carbon transition. The theoretical model links sustainable industrialization, sustainable remediation, circular supply chain governance, and food security. The empirical proxy model uses the available 455-response dataset to estimate IND -> DIC -> SER, where IND represents industrialization intensity, DIC represents digital-institutional governance capability, and SER represents social-economic resilience as a proxy for food-security resilience. The CFA results support measurement quality: all standardized loadings exceed .778, all alpha and CR values exceed .863 and .901 respectively, and AVE values exceed .646. Model fit is acceptable with chi-square/df = 2.108, CFI = .961, TLI = .951, RMSEA = .049, and SRMR = .038. Structural results show that IND predicts DIC (beta = .537), DIC predicts SER (beta = .424), and IND retains a direct effect on SER (beta = .337), all at $p < .001$. The mediation effect is significant (beta = .228, 95% CI [.178, .282]).

The conclusion is clear: industrialization contributes to resilience not only through direct economic and infrastructure effects but also through the governance capability represented by digital connectivity, logistics coordination, vocational support, and business-service access. For low-carbon food-security governance, this means that decarbonization and remediation should be accompanied by circular supply-chain standards, traceability systems, inter-agency coordination, and digital-institutional capacity building. Future research should measure sustainable remediation directly and estimate the full four-construct model. The next survey should include indicators for contaminated land restoration, safe waste handling, water-quality protection, remediation carbon efficiency, and remediation accountability. With those indicators, the full SI-SR-CSCG-FS model can be tested without proxy limitations.

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