Prioritizing Social Risk in Bangladesh's Frozen Shrimp Export Chain: A Policy-Augmented, Stage-Differentiated Screening Social Life Cycle Assessment, 2013 and 2022

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Submitted to

Dr. Md. Qamruzzaman

Professor

School of Business & Economics (SoBE) & Director, IBER

United International University

Submitted by

Muhotasim Mahin

111 222 005

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Dr. Md. Qamruzzaman

Professor

School of Business & Economics (SoBE), United International University

United City, Madani Ave, Dhaka 1212

Subject: **Submission of Project Report titled "Prioritizing Social Risk in Bangladesh's Frozen Shrimp Export Chain: A Policy-Augmented, Stage-Differentiated Screening Social Life Cycle Assessment, 2013 and 2022"**

Dear Sir,

I am pleased to submit my project report titled *"Prioritizing Social Risk in Bangladesh's Frozen Shrimp Export Chain: A Policy-Augmented, Stage-Differentiated Screening Social Life Cycle Assessment, 2013 and 2022,"* in partial fulfillment of the requirements of the Project course in the Bachelor of Business Administration program of the School of Business and Economics, United International University.

The report presents a descriptive-comparative, stage-differentiated screening social life cycle assessment of Bangladesh's frozen shrimp export chain for 2013 and 2022. Across six cradle-to-export-gate stages, it integrates labor-vulnerability indicators, trade-exposure weighting, and a Policy Response Capacity Index to identify raw social hotspots, examine changes in stage-level vulnerability, and classify governance-adjusted residual risk. The findings provide a structured basis for policy prioritization, supply-chain due diligence, and targeted intervention by exporters, processors, buyers, and public institutions.

I prepared this report under your supervision and incorporated your guidance on the study's scope, methodological refinement, and successive revisions. I respectfully submit it for your kind review and would welcome your feedback.

Yours sincerely,
Muhotasim Mahin
111 222 005

<u>Certification of Similarity Index</u>

This is to certify that the project report titled *"Prioritizing Social Risk in Bangladesh's Frozen Shrimp Export Chain: A Policy-Augmented, Stage-Differentiated Screening Social Life Cycle Assessment, 2013 and 2022,"* prepared by **Muhotasim Mahin** (ID: **111 222 005**), has been checked through Turnitin and has received a similarity index of **__________%** on **____________________**.

<u>Declaration of the Student</u>

I, **Muhotasim Mahin** (ID: **111 222 005**), hereby declare that the project report titled *"Prioritizing Social Risk in Bangladesh's Frozen Shrimp Export Chain: A Policy-Augmented, Stage-Differentiated Screening Social Life Cycle Assessment, 2013 and 2022"* is my original academic work and is submitted in partial fulfillment of the requirements of the Project course in the Bachelor of Business Administration program of the School of Business and Economics, United International University.

I further declare that this report was prepared under the academic supervision of Dr. Md. Qamruzzaman. All information, data, ideas, concepts, analyses, arguments, and interpretations drawn from published or unpublished sources have been properly acknowledged through appropriate in-text citations and the reference list.

This project report has not been submitted previously, in whole or in part, to any other university or institution for the award of any degree, diploma, certificate, or academic credit. I accept responsibility for the accuracy, integrity, and ethical conduct of the work and for compliance with the academic-integrity requirements of United International University.

I certify that I have exercised due care to ensure that all borrowed, adapted, paraphrased, or quoted material is properly attributed and that this report does not contain plagiarism, fabrication, falsification, or any other form of academic misconduct.

Muhotasim Mahin

111 222 005

Business Analytics & Finance and Fintech

Bachelor of Business Administration

School of Business and Economics

United International University

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His supervision also contributed substantially to my broader development as an undergraduate researcher. The research discipline and academic-writing experience developed under his guidance, including through my first research publication during Spring 2026, informed the preparation of this project report.

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Abstract

Purpose — This paper locates where social risk concentrates along Bangladesh's frozen shrimp export chain, how that profile shifted from 2013 to 2022, and where vulnerability meets weak governance.

Design/methodology/approach — A descriptive-comparative screening social life cycle assessment (sLCA) spans six cradle-to-export-gate stages. Social Hotspot Scores from four ILOSTAT labor indicators are export-exposure weighted using WITS mirror-trade flows, adjusted by a Policy Response Capacity Index coded from USDOL narratives, with an exploratory Ward-clustering check.

Findings — Processing and freezing records the highest raw hotspot in both years (SHS = 85.27 in 2013 and 56.00 in 2022), despite the anticipated vulnerability of upstream informal interfaces. All stages decline unevenly, reordering the stage ranking, and the observed shift is driven chiefly by child-related rather than adult labor indicators. Exposure weighting elevates export-linked stages. After governance adjustment, policy priority shifts away from the processing node toward weakly governed upstream and logistics interfaces; the Critical residual-risk category contains three stages in both years, with grow-out farming replaced by export logistics in 2022.

Research limitations/implications — Sectoral proxies rank relative risk without verifying firm-level conditions; the contrast is descriptive, not causal, requiring worker-level validation and longer panels.

Practical implications — The residual-risk map turns sLCA into a sourcing instrument, redirecting assurance and supplier-development effort from the audited processing node toward the upstream and logistics interfaces.

Social implications — Priority should follow residual risk, not raw hotspots: extending inspection into informal handling, reactivating child-labor remediation, and formalizing pond-side interfaces protect least-protected workers.

Originality/value — Integrating stage-resolved social hotspots, export exposure, and producing-country governance into one residual-risk classification positions sLCA as the diagnostic layer socially sustainable supply chain management presupposes but rarely obtains.

Keywords — Social life cycle assessment; Socially sustainable supply chain management; Social hotspots; Supply chain due diligence; Multi-tier supply chains; Bangladesh shrimp exports

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List of Acronyms & Abbreviations

Acronym	Full Form
AE1–AE5	Analytical Expectations 1–5
COVID-19	Coronavirus Disease 2019
DFID	Department for International Development
EMDE	Emerging Market and Developing Economy
EPZ	Export Processing Zone
ESC	Economic, Social, and Cultural
ESG	Environmental, Social, and Governance
EU	European Union
EWSHS	Exposure-Weighted Social Hotspot Score
FAO	Food and Agriculture Organization of the United Nations
GRR	Governance-Adjusted Residual Risk
HHI	Herfindahl–Hirschman Index
HS	Harmonized System
I1–I4	Core social-risk indicator codes: I1 = Informality; I2 = Weekly Working Hours; I3 = Child Labor; I4 = Hazardous Child Work
ILO	International Labour Organization
ILOSTAT	International Labour Organization Statistics Database
ISIC	International Standard Industrial Classification of All Economic Activities
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCT	Life Cycle Thinking
LkSG	Lieferkettensorgfaltspflichtengesetz
OECD	Organisation for Economic Co-operation and Development
OECD–FAO	Organisation for Economic Co-operation and Development–Food and Agriculture Organization

Acronym	Full Form
P1–P5	Policy Response Capacity dimensions: P1 = Legal Coverage; P2 = Enforcement Capacity; P3 = Hazardous-Work Recognition; P4 = Remediation and Social Protection; P5 = Due-Diligence Orientation
PPP	Purchasing Power Parity
PRCI	Policy Response Capacity Index
RQ1–RQ5	Research Questions 1–5
S1–S6	Supply-chain stage identifiers: S1 = Hatchery and Nursery Inputs; S2 = Feed and Farm Inputs; S3 = Grow-Out Farming; S4 = Harvest and Primary Handling; S5 = Processing and Freezing; S6 = Export Logistics
SDG	Sustainable Development Goal
SHS	Social Hotspot Score
SLA	Sustainable Livelihoods Approach
sLCA	Social Life Cycle Assessment
SSCM	Socially Sustainable Supply Chain Management
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme
UNICEF	United Nations Children's Fund
USD	United States Dollar
USDOL	U.S. Department of Labor
WDI	World Development Indicators
WITS	World Integrated Trade Solution
WP	Working Poverty Rate

Chapter 1: Introduction

1.1 Background and Research Context

Paul and Vogl (2011) and Alam (2024) characterize Bangladesh’s frozen shrimp export chain as a vertically fragmented agri-food and agro-industrial system spanning hatchery and nursery inputs, feed-and-input supply, grow-out pond cultivation, harvest and primary handling, processing and freezing, and cold-chain export logistics. Each stage couples distinct labor regimes—smallholder pond operations, informal handling and drying interfaces, industrial wage employment, and contracted logistics—within a single export commodity coded as HS 030613. This stage heterogeneity creates a natural case for Life Cycle Thinking, which evaluates impacts across the full product chain rather than at any single production node, thereby avoiding the displacement of social risk between stages that single-node analyses permit. Under the 2020 UNEP Guidelines (Tragnone, D'Eusanio, & Petti, 2022; United Nations Environment Programme, 2020), this logic is foundational to Social Life Cycle Assessment (sLCA).

Aquatic-food systems sit at the center of contemporary sustainable production and consumption agendas, with aquaculture now exceeding capture fisheries in production volume and shrimp ranking among the highest-value traded aquatic commodities (Food and Agriculture Organization of the United Nations, 2022; Ruiz-Salmón et al., 2021). Applying Life Cycle Thinking to this commodity links upstream agri-food cultivation with downstream agro-industrial processing and export logistics within a single product chain, positioning the study as a stage-resolved social-risk diagnostic for socially sustainable supply chain management.

The relevance of stage-differentiated assessment is amplified for export-oriented commodities whose social risks are unevenly distributed across upstream cultivation and downstream processing yet aggregated under a single trade code at the customs border (Decker Sparks, Matthews, Cárdenas, & Williams, 2022; Marschke et al., 2021). For Bangladesh, the shrimp chain operates within a labor-market context characterized by high agricultural informality, child engagement in fishing, drying, and processing activities, and persistent enforcement gaps; the U.S. Department of Labor (2014, 2023) documents these conditions across successive country profiles. These features locate the chain squarely within the analytical concern of sustainable agri-food and agro-industrial systems for which screening sLCA was designed (D'Eusanio, Zamagni, & Petti, 2019; Tragnone et al., 2022).

1.2 Problem Statement: Social Invisibility in Seafood Supply Chains

Marschke and Vandergeest (2016) and Decker Sparks et al. (2022) show that social risks in fragmented seafood supply chains are systematically difficult to observe because labor flows across pond-side handling, informal drying yards, processing plants, and subcontracted logistics interfaces, only some of which fall within the perimeter of factory inspection or buyer audit. Existing environmental and export-oriented analyses of shrimp commodities concentrate on production-stage performance and rarely identify where social vulnerability is concentrated along the chain (Farmery et al., 2021; Ruiz-Salmón et al., 2021). The resulting chain-level information asymmetry leaves aggregate national or sectoral indicators masking intra-chain variation, while firm-level audits cover only registered nodes. Setting intervention priorities therefore requires resolving social risk at the stage level rather than at the national-sector aggregate (Sureau, Mazijn, Garrido, & Achten, 2018; United Nations Environment Programme, 2020).

Three structural features reinforce the invisibility of stage-level social risk in seafood chains. First, social-sustainability research has historically lagged environmental-sustainability research in seafood, producing thinner diagnostic infrastructure for labor, livelihood, worker voice, and remediation dimensions (Alexander & Kelling, 2024; Finkbeiner, Fitzpatrick, & Yadao-Evans, 2021). Second, voluntary corporate-responsibility tools concentrate audit attention on registered processing nodes and underrepresent informal labor interfaces, marginalizing the workers most exposed to social risk (Decker Sparks et al., 2022). Third, public statistical infrastructure typically reports labor indicators at sectoral aggregates rather than at chain-stage granularity, leaving analysts dependent on proxy-based screening when stage-level worker inventories are unavailable (Benoît Norris, Norris, & Aulisio, 2014; Wu, Yang, & Chen, 2014).

1.3 Bangladesh Shrimp Sector and Export Profile

Bangladesh’s frozen shrimp sector occupies a strategically meaningful position in the country’s export economy and in global seafood markets. Alam (2024) and Belton, van Asseldonk, and Bush (2017) report that shrimp farming covers approximately 180,000 to 185,000 hectares in the southern coastal districts of Khulna, Satkhira, and Bagerhat, and that the sector supplies livelihoods to several million workers across hatcheries, ponds, depots, and processing plants.

World Integrated Trade Solution (WITS) mirror data for HS 030613—frozen shrimps and prawns—record total reported imports from Bangladesh of approximately USD 491 million in 2013, declining to approximately USD 346 million in 2022 (World Bank, 2026c). Quantity exported shows a steeper decline, falling from 48.8 thousand tonnes to 27.2 thousand tonnes across the same window. The European Union remained the dominant import region in both observation years, with Germany, the Netherlands, Belgium, and the United Kingdom forming the core European destination set; the United States and Japan retained material but reduced import shares between 2013 and 2022 (Alam, 2024; World Bank, 2026c).

Importer-market concentration, measured by the Herfindahl–Hirschman Index (HHI) calculated from partner-level import-value shares, rose from approximately 1,090 in 2013 to approximately 1,314 in 2022, while the top-five-importer share rose from 66.3 percent to 75.0 percent (World Bank, 2026c). As Alam (2024) and the Food and Agriculture Organization of the United Nations (2022) document, the intervening period covered global commodity stress, food-safety compliance episodes in EU and U.S. markets, the COVID-19 pandemic, and competitive displacement by larger Vannamei-based exporters such as Ecuador, India, and Vietnam, whose production scale and unit-cost structures have reshaped the global shrimp trade. Alam (2024) further notes that Bangladesh's residual position in this market is anchored in tiger prawn (*Penaeus monodon*) and giant freshwater prawn (*Macrobrachium rosenbergii*) supply, with vannamei pilots only recently authorized at limited scale. Declining export value, rising buyer concentration, and persistent labor-vulnerability documentation co-occur in the Bangladesh frozen shrimp commodity, locating commercial salience and screened social risk at the same set of chain stages (Alam, 2024; U.S. Department of Labor, 2014, 2023).

1.4 Research Gap and Study Positioning

Three substantive evidence gaps motivate the present study. First, the reviewed literature does not provide a stage-differentiated screening sLCA of Bangladesh's frozen shrimp export chain comparing 2013 and 2022 using open sectoral labor, trade, and governance data; existing seafood and aquaculture sLCA work concentrates on environmental dimensions and reports only fragmentary stage-level social-risk decomposition (Alexander & Kelling, 2024; Farmery et al., 2021; Ruiz-Salmón et al., 2021). Second, U.S. Department of Labor (2014, 2023) and International Labour Organization and United Nations Children's Fund (2021) document persistent child-labor, hazardous-work, and enforcement gaps in Bangladesh at the country level but do not produce a stage-level hotspot score that integrates these governance findings with sectoral labor-vulnerability indicators. Third, OECD and Food and Agriculture Organization of the United Nations (2016) and Macchi and Bright (2020) specify a five-step risk-identification-and-mitigation cycle but provide no quantitative scaffold linking screened social risk to producing-country governance capacity at chain-stage granularity. The present study addresses these gaps through a screening and prioritization model that integrates sectoral proxy indicators, bilateral trade exposure, and country-level governance evidence into a stage-level residual-risk classification, computed for 2013 as a pre-pandemic baseline and 2022 as a post-pandemic comparison year (Belton et al., 2021; United Nations Children’s Fund, 2021).

The positioning is non-causal by design. Following Saisana and Saltelli (2011), Greco, Ishizaka, Tasiou, and Torrisi (2019), and Tragnone et al. (2022), cross-sectional secondary indicators do not support counterfactual identification of pandemic effects, sectoral-policy effects, or buyer-side due-diligence effects, and composite-score outputs are interpreted as relative-risk signals rather than verified worker-level conditions. Accordingly, the contribution sought is a transparent, reproducible, two-period, stage-differentiated, policy-augmented prioritization tool rather than a causal estimate of any single intervention, shock, or governance reform. This framing is consistent with the methodological direction of recent agri-food sLCA scholarship, which has called for the integration of governance-side variables alongside indicator-side variables in screening assessments where producing-country institutional capacity shapes the corrective potential of identified risks (D'Eusanio et al., 2019; Tragnone et al., 2022).

1.5 Research Questions and Objectives

The study addresses five non-causal research questions. RQ1: Which stages of Bangladesh's frozen shrimp export chain registered the highest screened social risk in 2013 and 2022, measured by a stage-level Social Hotspot Score (SHS) constructed from informality, weekly working hours, child labor, and hazardous child work? RQ2: How did the stage-level hotspot profile shift between the two observation years? RQ3: Which indicators—informality, weekly working hours, child labor, or hazardous child work—drove the observed shifts under additive decomposition of the SHS? RQ4: Does integrating frozen-shrimp export exposure—export value, export quantity, and importer-market concentration—reorder the policy-priority ranking relative to the unweighted SHS ranking? RQ5: Which stages combine high screened social risk with weak Policy Response Capacity, forming the Critical residual-risk category under governance-adjusted classification?

The corresponding objectives are to specify the cradle-to-export-gate chain boundary, construct the SHS using min–max normalization and equal-weight aggregation, compare the 2013 and 2022 stage-level hotspot profiles, decompose observed score changes by indicator, incorporate export-exposure weighting, score policy-response capacity, and identify stage-level intervention priorities.

The research questions are deliberately phrased as hotspot-identification, decomposition, and prioritization queries rather than as causal-effect questions. They are answered through descriptive-comparative analysis, indicator decomposition, and matrix classification, rather than through causal-effect estimation. The objectives sequence accordingly proceeds from boundary specification and indicator selection, through composite-score construction and temporal comparison, to exposure-weighting, policy-response scoring, and residual-risk classification. This design supports replication, sensitivity analysis, and ranking-stability assessment without making causal claims about pandemic effects, sectoral-policy effects, or buyer-side due-diligence effects on the observed indicator levels.

Section 3 translates RQ1–RQ5 into five theory-informed analytical expectations (AE1–AE5) that guide interpretation of the descriptive-comparative results without functioning as causal hypotheses or significance-tested propositions.

1.6 Contribution of the Study

This study makes four contributions to social life cycle assessment and socially sustainable supply chain management in agri-food and agro-industrial systems. The first is theoretical: it connects screening sLCA to the socially sustainable supply chain management literature, extending that literature beyond the buyer–supplier dyad to the full multi-stage chain. That literature specifies the firm-side instruments—assessment, collaboration, and supplier development—for acting on identified risk but rarely provides the stage-resolved evidence to target them across tiers, which a stage-differentiated sLCA supplies (D'Eusanio et al., 2019; Villena & Gioia, 2020; Yawar & Seuring, 2017).

The second is methodological: it develops a policy-augmented, stage-differentiated screening sLCA that integrates a Social Hotspot Score, export-exposure weighting, and a Policy Response Capacity Index—scoring legal coverage, enforcement capacity, hazardous-work recognition, remediation access, and due-diligence orientation—into a governance-adjusted residual-risk classification. This adds a producing-country governance-response axis beyond the raw vulnerability ranking conventional screening sLCA returns, and supplements the additive score with exploratory Ward clustering to describe broad stage-year risk profiles (OECD and Food and Agriculture Organization of the United Nations, 2016; United Nations Environment Programme, 2020).

The third is empirical: it supplies a two-period, stage-level hotspot comparison of Bangladesh's frozen shrimp chain for 2013 and 2022, covering hatchery and nursery inputs, feed-and-input supply, grow-out pond cultivation, harvest and primary handling, processing and freezing, and cold-chain export logistics—a stage-resolved analysis that remains underdeveloped in the reviewed literature. It is built entirely from open labor, trade, and governance data on a cradle-to-export-gate boundary that surfaces the post-harvest, processing, and logistics interfaces a farm-gate scope omits (Ruiz-Salmón et al., 2021).

The fourth is practical: by separating raw labor vulnerability, export-exposure salience, and governance-response capacity—signals a single facility audit may conflate—it yields a prioritized, stage-resolved map that shows regulators, buyers, processors, and exporters where due-diligence effort should concentrate, not where monitoring is already densest (Decker Sparks et al., 2022; OECD and Food and Agriculture Organization of the United Nations, 2016).

Because every input is open, the core indicator aggregation is equal-weighted, and the governance rubric is documented—ILOSTAT labor indicators, WITS HS 030613 mirror-import data, World Bank employment context, and USDOL governance evidence harmonized into an auditable model—the framework provides a reproducible template for applying policy-augmented screening sLCA to other export commodities where stage-level worker inventories are unavailable. This contribution is deliberately bounded to a descriptive-comparative, relative-risk register: it supplies a screening-and-prioritization tool, not a causal estimate of any single shock, sectoral policy, or governance reform (Tragnone et al., 2022).

Chapter 2: Theoretical Foundation and Literature Review

2.1 Theoretical Foundation

Social Life Cycle Assessment (sLCA) anchors the theoretical foundation of this study. Following the UNEP sLCA Guidelines and the broader four-phase life-cycle architecture associated with ISO 14040/14044, sLCA evaluates social and socioeconomic risks through goal and scope definition, social life-cycle inventory, impact assessment, and interpretation (International Organization for Standardization, 2006a, 2006b; United Nations Environment Programme, 2020), with impacts organized across six stakeholder categories: workers, local community, value chain actors, consumers, society, and children (Benoît Norris et al., 2014; Tragnone et al., 2022). Petti, Serreli, and Di Cesare (2018) and Sureau et al. (2018) show that this stage-differentiated logic is well-suited to fragmented agri-food and agro-industrial chains because it exposes the distribution of social vulnerability across activities that aggregate national or single-firm analyses obscure. For the present study, sLCA supplies the chain-boundary specification, the worker-subcategory architecture from which the four core indicators (informality, weekly hours, child labor, hazardous child work) are drawn, and the screening logic that legitimizes sectoral-proxy use when stage-specific firm-level data are unavailable (Ramos Huarachi, Piekarski, Puglieri, & de Francisco, 2020; Wu et al., 2014).

The Sustainable Livelihoods Approach (SLA) functions as a complementary interpretive lens. Originating in Chambers and Conway (1992) and operationalized through the Department for International Development (1999) capitals framework, SLA conceptualizes livelihood security through five capitals—human, social, financial, physical, and natural—mediated by institutional structures and vulnerability contexts. Scoones (2009) and Natarajan, Newsham, Rigg, and Suhardiman (2022) situate these capitals within evolving institutional and shock contexts, and applied alongside sLCA, SLA explains why informality, child engagement in work, excessive working hours, and weak labor protection function as livelihood-erosion mechanisms by depleting human and financial capital and weakening household capacity to absorb shocks.

The pairing accommodates both system-level (sLCA) and household-level (SLA) framings without proliferating theoretical commitments. Recent integrations in agri-food research demonstrate that vulnerability indicators encoded in sLCA inventories acquire interpretive depth when read through livelihoods lenses (D'Eusanio et al., 2019; Natarajan et al., 2022). For the shrimp chain, the integration is consequential because labor relations vary qualitatively across stages: Belton et al. (2017) and Marschke et al. (2021) document that smallholder pond operations resemble household-livelihood systems, factory-based processing operates under industrial wage relations, and primary handling and fish drying are dominated by informal piece-rate arrangements with weak protection coverage.

Both theories admit non-causal, descriptive–comparative use, supporting the study's framing as hotspot identification and prioritization rather than causal effect estimation. Benoît Norris et al. (2014) and Tragnone et al. (2022) show that sLCA characterization is widely deployed for screening, with composite-score outputs interpreted as relative-risk signals rather than verified worker-level conditions. Scoones (2009) and Natarajan et al. (2022) establish that SLA is fundamentally diagnostic, supporting policy framing without claiming counterfactual identification. **Table *1*** summarizes the study's theoretical foundation, linking each anchoring theory to its target variables and the justification for inclusion.

Table 1. Theoretical foundation: theory, target variables, and justification

Theory	Target variables	Justification
Social Life Cycle Assessment (UNEP, 2020; ISO 14040/14044)	Worker-subcategory indicators: informality (I1), weekly working hours (I2), child labor (I3), hazardous child work (I4); chain-boundary scope (cradle-to-export-gate); stakeholder categories (workers, value chain actors)	Provides chain-boundary specification, stakeholder-subcategory architecture, and screening logic for stage-differentiated assessment of fragmented agri-food chains where direct stage-level worker data are unavailable; supports proxy-based composite scoring for relative-risk ranking
Sustainable Livelihoods Approach (Chambers & Conway, 1992; DFID, 1999; Scoones, 1998, 2009; Natarajan et al., 2022)	Livelihood capitals shaped by labor conditions: human capital (education, health), financial capital (income stability), social capital (collective protection); vulnerability context (shocks, trends, seasonality)	Explains why each sLCA worker indicator translates into household-level livelihood erosion; provides interpretive grounding for hotspot scores as policy-actionable signals; supports stage-specific framing where labor relations differ qualitatively across the chain

2.2 Literature Review

2.2.1 Life Cycle Thinking and sLCA in Agri-Food Systems

Life Cycle Thinking (LCT) examines impacts across the full product chain rather than at a single production site, preventing intervention strategies from displacing rather than reducing risk (United Nations Environment Programme, 2020). sLCA extends this logic to social and socioeconomic impacts, following the four-phase ISO life-cycle architecture: goal and scope, inventory, impact assessment, and interpretation (Petti et al., 2018; Sureau et al., 2018). Tragnone et al. (2022) and Ramos Huarachi et al. (2020) note that the 2020 UNEP Guidelines refined two frontiers relevant to this study: a clarified subcategory taxonomy of forty subcategories across the six stakeholder groups (United Nations Environment Programme, 2020), and explicit accommodation of Type I (reference-scale) and Type II (impact-pathway) characterization, with screening anchored in Type I logic where worker-level evidence is limited. Empirical sLCA applications in agri-food and aquaculture systems have demonstrated the diagnostic value of stage-level decomposition for revealing risk concentrations that aggregate indicators conceal (D'Eusanio et al., 2019; Iribarren, Moreira, & Feijoo, 2010).

Ruiz-Salmón et al. (2021) document that seafood assessments require careful treatment of system boundaries, allocation, and processing stages, while social dimensions remain less developed than environmental ones. Synthesizing agri-food applications, Arcese, Fortuna, and Pasca (2023) report heavy reliance on generic databases and reference-scale methods with limited stakeholder engagement, reinforcing both the feasibility and the interpretive limits of proxy-based screening designs. For Bangladesh's shrimp chain, Sureau et al. (2018) and the broader LCT/sLCA architecture (United Nations Environment Programme, 2020) provide the analytical backbone of stage-differentiated comparison and motivate the assignment of agriculture, industry, and services-mapped indicators to chain stages whose direct labor profiles are not separately measured.

Recent agri-food sLCA work has consolidated three methodological positions relevant to the present application. First, the screening sLCA mode is now well-established as a legitimate analytical layer for prioritization where primary firm-level data collection is infeasible, with reference-scale characterization producing relative rather than absolute social-risk signals (Ramos Huarachi et al., 2020; Tragnone et al., 2022). Second, sectoral and country-level proxies drawn from databases such as the Social Hotspots Database have been routinely deployed for chains where worker-level inventory data are absent (Benoît Norris et al., 2014). Third, D'Eusanio et al. (2019) and Macombe, Leskinen, Feschet, and Antikainen (2013) show that agri-food sLCA increasingly integrates governance-side variables alongside indicator-side variables, recognizing that headline labor conditions are jointly shaped by labor-demand structure and regulatory enforcement capacity. These developments collectively support a screening-and-prioritization design that combines sectoral proxy indicators with policy-response evidence, as proposed in this study.

Notwithstanding methodological progress, sLCA in seafood and aquaculture chains remains underdeveloped relative to terrestrial agri-food applications, with comparatively few stage-differentiated studies of frozen seafood export commodities and almost none combining bilateral trade-flow exposure with governance-capacity adjustment (Farmery et al., 2021; Iribarren et al., 2010). The present study addresses this thin evidence base by foregrounding stage-level decomposition and policy augmentation in a single export commodity for which child labor, informality, and enforcement gaps are extensively documented (U.S. Department of Labor, 2014, 2023).

2.2.2 Social Risks in Aquaculture and Seafood Supply Chains

Social risk in seafood and aquaculture chains concentrates around six recurrent dimensions: informal employment, long working hours, child engagement in work, hazardous task exposure, subcontracting and labor-intermediary opacity, and weak grievance and remediation infrastructure (Farmery et al., 2021; Marschke et al., 2021). Recent reviews position seafood social sustainability around livelihoods, human rights, worker voice, equitable benefit sharing, community well-being, and regional development, while documenting that these dimensions remain less developed than environmental sustainability indicators in the seafood literature (Alexander & Kelling, 2024). Belton et al. (2017) and the Environmental Justice Foundation (2014) show that these dimensions cluster particularly tightly in stages where production is fragmented across small operations, where work is paid by piece rather than time, and where the regulatory perimeter is porous—conditions that recur in upstream pond cultivation, primary handling, fish drying, and informal logistics interfaces.

Bangladesh’s frozen shrimp chain presents a documented case of this wider seafood labor-risk profile. The U.S. Department of Labor (2014, 2023) documents child labor and hazardous work in shrimp collection, drying, and processing, alongside categorical worst forms including forced labor in fish drying. Persistence of these findings across the 2013 and 2022 reports indicates that the risk profile is structural rather than transient (International Labour Organization and United Nations Children's Fund, 2021; U.S. Department of Labor, 2023).

The fragmentation of seafood chains complicates risk attribution because labor passes through multiple ownership and contractual interfaces between cultivation and export. Marschke and Vandergeest (2016) and Marschke et al. (2021) document a pattern in Asian aquaculture in which hazard exposure migrates from formal processing—where inspection and audit infrastructure is comparatively dense—to upstream and intermediate stages where intermediaries, depots, and informal handling sites are weakly regulated. This displacement effect is particularly visible in shrimp chains, where pre-processing handling, sorting, and drying activities sit between farms and inspected processing plants and recruit casual, often female and child labor (Environmental Justice Foundation, 2014; Paul & Vogl, 2011). Subcontracting and labor-broker arrangements further obscure responsibility lines, weakening the leverage of buyer audits that focus on registered processing nodes (Environmental Justice Foundation, 2014; OECD and Food and Agriculture Organization of the United Nations, 2016). Combined with the well-documented depression of farm-gate prices in price-taking smallholder shrimp regions, these structural features generate both indicator-level and chain-position risk concentrations that cannot be resolved by single-stage policy interventions.

The implications for stage-differentiated screening are direct: chain stages cannot be assumed to share the social risk profile of their parent sector, but sectoral indicators provide defensible relative-risk approximations where stage-specific worker data are absent (Sureau et al., 2018; Wu et al., 2014). In Bangladesh's shrimp chain, this proxy logic is reinforced by the documentary record—USDOL reports across both observation years identify shrimp-specific labor concerns yet do not provide quantitative stage-level worker inventories, leaving sectoral-proxy approaches as the only feasible quantitative screening route (U.S. Department of Labor, 2014, 2023).

2.2.3 Bangladesh Labor Governance and Child-Labor Context

The U.S. Department of Labor (2014, 2023) classifies Bangladesh as having made "moderate advancement" in 2013 but only "minimal advancement—efforts made but regression in practices that delayed advancement" in 2022. The downgrade is consistent with a pattern in which legal-framework expansion has outpaced enforcement, social-program coverage, and informal-sector reach. Between the two reports, Bangladesh extended the hazardous-work list to include dried fish manufacturing, street-based child labor, brick and stone production and transport, informal garment production, and waste management (U.S. Department of Labor, 2023). Yet several structural weaknesses persisted: the Bangladesh Labor Act's exclusion of small farms with fewer than ten workers, domestic work, and ocean-going vessels; a maximum penalty for child-labor violations of approximately USD 47 per offense; and an inspectorate of approximately 400 officers covering a workforce exceeding 74 million (International Labour Organization and United Nations Children's Fund, 2021; U.S. Department of Labor, 2023). Public reporting of criminal-enforcement statistics related to child labor and trafficking remains absent for the 2022 cycle (U.S. Department of Labor, 2023).

These institutional features have direct implications for stage-level social-risk screening of the shrimp chain. The legal-coverage gap leaves the chain segments most likely to host child and informal labor—small ponds, primary handling, drying, and informal logistics—largely outside enforceable inspection regimes (Belton et al., 2017; U.S. Department of Labor, 2014). The Export Processing Zone (EPZ) Labor Rules require labor inspectors to provide prior notice via "intimation" before inspecting EPZ factories, weakening unannounced-inspection capacity at the most formalized end of the chain (U.S. Department of Labor, 2023). Reciprocal referral mechanisms between labor inspection and child-protection services have been intermittently active and were not functional in 2022 (U.S. Department of Labor, 2023). Although programs such as the Elimination of Hazardous Child Labor and Child-Sensitive Social Protection in Bangladesh have provided remediation pathways, their reach into informal supply-chain segments remains constrained (U.S. Department of Labor, 2023; United Nations Children's Fund, 2021).

The institutional record across the two observation years justifies treating Bangladesh's labor governance as a dimension of chain-level social risk rather than a fixed background condition. The 2013–2022 contrast reveals not uniform improvement but selective, sectorally uneven advancement coupled with persistent enforcement gaps (International Labour Organization and United Nations Children's Fund, 2021; U.S. Department of Labor, 2014, 2023). For a stage-differentiated screening sLCA, this implies that observed indicator changes between the two years reflect a composite of labor-market structural change, sectoral employment recomposition, and governance-response variation, none of which can be disentangled causally from cross-sectional secondary data. The institutional record therefore supports the construction of a Policy Response Capacity Index alongside the labor indicator composite, rather than the inference of governance effects from indicator change.

2.2.4 Pre-COVID Baseline and Post-Pandemic Vulnerability Literature

A comparison anchored in 2013 and 2022 spans the COVID-19 pandemic, which the literature documents as a sharp shock to labor markets, household income, school enrollment, and supply-chain operation in low- and middle-income economies (International Labour, 2022; United Nations Children's Fund, 2021). Cross-country evidence indicates pandemic-period reversals in child-labor reductions and intensifications of informal-employment shares, with school closures associated with increased child engagement in work in households experiencing income shocks (Genoni, Khan, Krishnan, Palaniswamy, & Raza, 2020; International Labour Organization and United Nations Children's Fund, 2021). For Bangladesh specifically, Genoni et al. (2020) document that ready-made garment order cancellations, shrimp export disruptions, and rural reverse migration generated income shocks that the literature associates with increases in household labor-supply pressure and school-attendance volatility. These dynamics imply that post-pandemic indicator levels reflect a composite of long-run structural transformation and pandemic-induced disturbances, neither of which can be cleanly separated from cross-sectional indicator data.

The pandemic literature also documents that supply-chain disruptions in seafood and apparel chains exposed governance and remediation infrastructure to stress, with mixed evidence on whether the stress catalyzed governance reform or eroded enforcement capacity (International Labour, 2022; Marschke et al., 2021). Belton et al. (2021) provide multi-country evidence specific to aquatic food value chains, documenting pandemic-era disruptions in production, transport, input availability, demand, and trading arrangements, with actors adapting through alternative sales channels and reduced operations rather than uniform contraction. For Bangladesh's shrimp sector, anecdotal evidence and small-sample studies report cold-chain interruptions, depressed farm-gate prices, and reduced processing throughput, but no comprehensive worker-level survey for the 2020–2022 window is publicly available (Belton et al., 2017; Marschke et al., 2021). This evidentiary gap reinforces the analytical decision to frame the 2013–2022 comparison as descriptive—pre-pandemic baseline against post-pandemic comparison year—rather than causal–counterfactual. The COVID literature accordingly informs interpretation but does not authorize attribution; observed shifts in stage-level hotspot scores between the two years are read as composite signals rather than as estimates of pandemic-effect magnitude, consistent with the screening sLCA literature's emphasis on relative-risk signaling (Benoît Norris et al., 2014; Tragnone et al., 2022).

2.2.5 Proxy Indicators, Hotspot Screening, and Composite Index Methods

Proxy-based screening occupies a recognized methodological position in social-impact assessment when worker-level or firm-level inventory data are unavailable (Benoît Norris et al., 2014; Wu et al., 2014). Sureau et al. (2018) and Petti et al. (2018) show that sectoral and country-level proxies derived from labor-force surveys, modeled employment estimates, and governance reports support relative-risk ranking even where direct measurement is infeasible. Proxy approaches do not estimate verified worker conditions; they generate screening signals whose interpretive value rests on transparent indicator selection, defensible normalization, and explicit weight-sensitivity testing (Greco et al., 2019; Saisana & Saltelli, 2011).

Recent application-based evidence reinforces this caveat. Díez-Hernández, Carreira-Barral, López-de-Foronda, and Martel-Martín (2026) show that database-assisted screening sLCA can identify latent supply-chain social risks where direct inventory data are incomplete, but that generic country–sector reference data, static assumptions, and insufficient contextualization may bias the interpretation of social-risk profiles. These limitations do not invalidate proxy-based screening; rather, they discipline its use. In the present study, SHS outputs are interpreted as relative-rank screening signals rather than verified condition assessments, and the Policy Response Capacity Index contextualizes generic-data bias within Bangladesh's frozen shrimp export-chain policy environment.

Nardo et al. (2008) and Becker, Saisana, Paruolo, and Vandecasteele (2017) establish that composite-index construction in this tradition follows a four-step protocol: indicator selection guided by conceptual fit and data quality, normalization to a common scale (most often min-max), aggregation under stated weights, and sensitivity testing across alternative weight sets. Min-max normalization is preferred for screening composites because it preserves interpretable bounds and supports equal-weight aggregation, which serves as a defensible default when expert weight elicitation is not feasible (Greco et al., 2019; Saisana & Saltelli, 2011).

The composite-index literature documents three robustness practices that screening indices should support. First, sensitivity to alternative normalization (z-score, distance-to-frontier, ranking) and aggregation (additive, geometric) functions reveals whether substantive conclusions depend on functional choice (Becker et al., 2017; Greco et al., 2019). Second, weight-perturbation analysis, including Monte Carlo simulation across plausible weight distributions, documents the stability of stage-level rankings under uncertainty about analyst-imposed weights (Becker et al., 2017; Saisana & Saltelli, 2011). Third, indicator-inclusion sensitivity—running the composite with and without contested indicators—isolates whether single indicators drive results, an especially important check for hazardous child work, whose data quality varies by reporting cycle (Greco et al., 2019; Nardo et al., 2008). Composite scores are accordingly interpreted as relative-rank signals rather than absolute measurements, with policy use directed toward priority-setting and triage rather than precise impact quantification (Saisana & Saltelli, 2011; Tragnone et al., 2022).

2.2.6 Policy-Response, Due-Diligence, and Supply-Chain Management Literature

Supply-chain due diligence has shifted from voluntary corporate-responsibility framing to a layered system combining hard-law mandates, soft-law guidance, and government supply-chain transparency tools (OECD and Food and Agriculture Organization of the United Nations, 2016; United Nations, 2011). The OECD-FAO Guidance for Responsible Agricultural Supply Chains (OECD and Food and Agriculture Organization of the United Nations, 2016) specifies a five-step due-diligence cycle—policy commitment, risk identification, mitigation, performance monitoring, and stakeholder communication—that aligns with screening sLCA outputs by providing actionable risk targets at chain-stage granularity. Government tools complement this architecture: the U.S. Department of Labor's Comply Chain aligns with this cycle by providing a step-by-step social-compliance protocol, while the Better Trade Tool identifies imports at heightened risk of child or forced labor (U.S. Department of Labor, 2014, 2023). Decker Sparks et al. (2022) nevertheless show that market-based seafood compliance tools can underrepresent worker participation, grievance access, and enforceable remediation where audits concentrate on registered processing nodes rather than informal labor interfaces. This finding motivates modeling policy-response capacity as a separate analytical dimension. Mandatory regimes—including the German Lieferkettensorgfaltspflichtengesetz and the amended EU Corporate Sustainability Due Diligence Directive—will raise the evidentiary standard covered companies must meet on upstream labor conditions (European Parliament and Council of the European Union, 2024a; Macchi & Bright, 2020; Smit et al., 2020).

A parallel management literature—socially sustainable supply chain management (SSCM)—examines the firm-side instruments through which buyers and suppliers act on the risks that due-diligence regimes oblige them to identify. Yawar and Seuring (2017) organize these responses into communication, compliance, and supplier-development strategies, and subsequent evidence specifies their boundary conditions: assessment-led approaches improve supplier social performance less reliably than collaboration (Alghababsheh & Gallear, 2021); lower-tier suppliers remain the least monitored and most hazardous links, with requirements cascading to sub-suppliers mainly where buyer leverage is high (Villena & Gioia, 2020; Wilhelm & Villena, 2021); and institutional uncertainty in producing countries conditions which practices take hold (Huq & Stevenson, 2020; Kelling, Sauer, Gold, & Seuring, 2021). Reviews of multi-tier social sustainability locate persistent tensions between commercial pressure and social compliance at the upstream tiers least visible to buyers (Alghababsheh & Gallear, 2022; Govindan, Shaw, & Majumdar, 2021), while emerging due-diligence statutes are reshaping supplier evaluation and its performance consequences (Kraft, Quayson, & Kellner, 2025; Samal & Jena, 2025). The field's binding constraint is informational: these instruments presuppose chain-specific, stage-resolved evidence of where social risk concentrates, which facility audits and aggregate sector indicators do not supply and which screening sLCA is positioned to provide (D'Eusanio et al., 2019).

Macchi and Bright (2020) and Marschke et al. (2021) emphasize that risk identification, by itself, is insufficient: governance capacity, enforcement density, and remediation infrastructure determine whether identified risks translate into corrective action. For producing-country contexts, this implies that the value of supply-chain screening tools depends on the receiving institutional environment. In Bangladesh, the persistence of legal-framework gaps, low penalty levels, weak inspection density, and intermittent referral mechanisms restricts the corrective potential of buyer-side due diligence acting alone (International Labour Organization and United Nations Children's Fund, 2021; U.S. Department of Labor, 2014, 2023). The implication for screening sLCA design is that hotspot scores acquire policy meaning only when paired with an explicit policy-response capacity assessment: stages with high inherent screened vulnerability and high GRR fall within the Critical category, whereas stages with high SHS but lower GRR are classified as Managed because stronger governance capacity reduces residual risk (OECD and Food and Agriculture Organization of the United Nations, 2016; Smit et al., 2020).

2.2.7 Literature Synthesis

Four positions consolidate from the reviewed literature, summarized in **Table *2***. First, social risk in fragmented seafood chains concentrates at upstream and informal-interface stages and persists across observation periods despite legal-framework expansion (Farmery et al., 2021; Marschke et al., 2021; U.S. Department of Labor, 2014, 2023). Second, stage-differentiated sLCA combined with sectoral proxy indicators provides a defensible screening route where worker-level inventory data are absent, with composite-index methods supplying the analytical scaffolding for ranking and prioritization (Petti et al., 2018; Saisana & Saltelli, 2011; Sureau et al., 2018). Third, screening outputs acquire policy traction only when paired with governance-capacity evidence (Macchi & Bright, 2020; OECD and Food and Agriculture Organization of the United Nations, 2016; Smit et al., 2020). Fourth, the SSCM literature specifies the firm-side response instruments—assessment, collaboration, and supplier development—but lacks the chain-specific, stage-resolved risk evidence needed to allocate them within a given export chain (Villena & Gioia, 2020; Yawar & Seuring, 2017).

Together these positions define a study niche that no current paper occupies for Bangladesh's frozen shrimp export chain: a two-period, stage-differentiated, policy-augmented screening sLCA that combines four sectoral labor indicators, bilateral trade-exposure data, and country-level governance evidence into a single residual-risk classification, run for both 2013 and 2022 to support pre-pandemic baseline against post-pandemic comparison-year analysis. Existing studies produce one or two of these components—stage-level sLCAs without policy augmentation, governance reviews without quantitative indicator integration, or single-year hotspot screens without temporal comparison—but no study integrates all three for the Bangladesh shrimp commodity. Nor does any study connect such screening evidence to the firm-level allocation decisions that the SSCM literature identifies. These positions jointly motivate the analytical framework and the five analytical expectations developed in the next section, in which the sLCA stakeholder–subcategory architecture supplies the indicator scaffold, the SLA capitals lens supplies the interpretive register, and the OECD-FAO due-diligence cycle supplies the policy-response adjustment layer.

Table 2. Summary of literature review

Author	Sample (Year)	Methods	Objectives	Findings
Petti, Serreli, & Di Cesare (2018)	sLCA literature 1996–2016	Systematic literature review	Map sLCA methodological evolution and indicator practices	Documented growth and inconsistency in sLCA practice; established taxonomy of subcategory and indicator approaches
Sureau, Mazijn, Garrido, & Achten (2018)	Published sLCA frameworks	Comparative review of frameworks	Classify social-issue criteria and indicators	Identified consensus on stakeholder categories but persistent variation in indicator operationalization across frameworks
Tragnone, D'Eusanio, & Petti (2022)	Agri-food sLCA studies	Bibliometric and content analysis	Assess what counts in agri-food sLCA characterization	Worker subcategory dominates; governance-side variables underrepresented; need for integration with policy evidence

Author	Sample (Year)	Methods	Objectives	Findings
Arcese, Fortuna, & Pasca (2023)	Agri-food supply-chain sLCA literature	Literature review and socioeconomic metric integration	Integrate socioeconomic metrics into agri-food supply-chain assessment	Agri-food sLCA relies heavily on generic databases and reference-scale methods with limited stakeholder engagement; socioeconomic metric integration remains underdeveloped
Ramos Huarachi et al. (2020)	sLCA publications, 1996–2019	Bibliometric review	Trace historical evolution and research trends	Type I screening assessments dominant; growing application in supply chains and developing-country contexts
Saisana & Saltelli (2011)	Composite indicators (review)	Methodological review and audit protocol	Establish best-practice protocol for composite indices	Set standards for normalization, weighting, and uncertainty/sensitivity analysis in composite scoring
Greco, Ishizaka, Tasiou, & Torrisi (2019)	Composite indicator literature	Systematic methodological review	Synthesize methodological framework	Structured comparison of normalization, weighting, and aggregation choices and their substantive consequences
Becker, Saisana, Paruolo, & Vandecasteele (2017)	OECD/JRC composite indices	Variance-based sensitivity analysis	Examine weights and importance	Nominal weights frequently differ from realized importance; supports routine sensitivity testing
Díez-Hernández et al. (2026)	Silver nanowire sLCA case (EU DIAGONAL project)	Database-assisted screening sLCA application	Adapt sLCA for low-TRL innovations and assess latent supply-chain risks	Database-assisted screening can illuminate latent social risks but generic data and static assumptions bias interpretation

Author	Sample (Year)	Methods	Objectives	Findings
				and constrain engagement with vulnerable regions
Marschke, Vandergeest, Havice et al. (2021)	Asian seafood workers, 2020	Mixed-methods, multi-site study	Assess COVID-19 vulnerabilities in seafood chains	Pandemic-era intensification of seafood-chain labor vulnerabilities; weakening of grievance and remediation infrastructure
Belton, van Asseldonk, & Bush (2017)	Bangladesh aquaculture, 2014–2016	Mixed-methods value-chain analysis	Analyze livelihood pathways	Differentiated livelihood outcomes across smallholder and commercial aquaculture stages; informal interfaces dominate upstream
Belton et al. (2021)	Aquatic food value chains, Asia & Africa, 2020	Multi-country rapid assessment	Document COVID-19 impacts and adaptations	Pandemic disruptions across production, transport, demand, and trade; heterogeneous adaptation rather than uniform contraction
Paul & Vogl (2011)	Coastal Bangladesh shrimp regions	Review and field assessment	Evaluate social and environmental impacts of shrimp farming	Persistent labor and livelihood vulnerabilities in coastal shrimp regions; subcontracting depresses farm-gate returns
Farmery et al. (2021)	Global blue economy literature	Conceptual review	Identify blind spots in blue-economy framings	Labor and livelihood dimensions underrepresented in blue-economy planning; seafood social risk requires explicit governance attention

Author	Sample (Year)	Methods	Objectives	Findings
Decker Sparks et al. (2022)	Voluntary seafood labor-governance tools	Critical governance analysis	Assess whether voluntary tools protect workers	Market-based compliance tools marginalize worker voice, grievance access, and enforceable remediation; audits concentrate on formal nodes
Finkbeiner, Fitzpatrick, & Yadao-Evans (2021)	Seafood value-chain ESC and women's rights	Conceptual/policy analysis	Argue for protection of ESC and women's rights in seafood chains	Post-harvest and informal segments concentrate gendered and ESC-rights risks often invisible to facility-level audits
Alexander & Kelling (2024)	Seafood social-sustainability literature	Rapid review	Map social-sustainability dimensions in seafood systems	Social dimensions (livelihoods, rights, voice, benefit sharing) remain less developed than environmental indicators in seafood research
Natarajan, Newsham, Rigg, & Suhardiman (2022)	SLA literature, post-2000	Conceptual review	Update SLA for 21st-century challenges	SLA retains diagnostic value when extended to incorporate climate, financialization, and digital labor dimensions
USDOL (2014, 2023)	Bangladesh, 2013 and 2022	Government documentary review	Assess worst-forms-of-child-labor effort	Bangladesh moved from "moderate" to "minimal" advancement; persistent governance and enforcement gaps documented across both reports
ILO (2021)	Global child labor estimates, 2020	Statistical estimation	Estimate global trends in child labor	First global rise in child-labor numbers in two decades; concentrated in

Author	Sample (Year)	Methods	Objectives	Findings
				agriculture and informal services
Yawar & Seuring (2017)	Supply-chain social-issue literature (review)	Systematic literature review	Map social issues, firm actions, and performance outcomes	Classifies firm responses as communication, compliance, and supplier development; social-performance outcomes remain under-theorized relative to actions
Govindan, Shaw, & Majumdar (2021)	Multi-tier SSCM literature (129 papers)	Systematic literature review	Identify social-sustainability tensions and develop a conceptual framework	Social-sustainability tensions concentrate at higher and sub-supplier tiers; multi-tier evidence for emerging economies remains scarce
Villena & Gioia (2020)	Multinationa l multi-tier supply chains	Multi-year field research (practitioner synthesis)	Examine and reduce social and environmental risk in lower supply-chain tiers	Lower-tier suppliers are the least monitored and most hazardous links; buyers must extend visibility and capability building beyond the first tier
Wilhelm & Villena (2021)	134 Chinese suppliers, electronics (2021)	Mixed methods (audit and company records, survey, archival data)	Identify when second-tier suppliers adopt sustainable procurement	Cascading to sub-suppliers occurs mainly where the buyer holds a large share of the supplier's business
Alghababsheh & Gallear (2021)	119 UK manufacturer s	Survey; structural equation modeling (social-capital theory)	Test assessment versus collaboration effects on supplier social performance	Collaboration improves supplier social performance more reliably than assessment; relational social capital strengthens the effect
Alghababsheh & Gallear (2022)	Social SSCM	Literature review	Synthesize adoption, approaches,	Maps assessment- and collaboration-based approaches

Author	Sample (Year)	Methods	Objectives	Findings
	literature (review)		and (un)intended outcomes of social SSCM	and their uneven, sometimes unintended, social outcomes at upstream tiers
Kelling, Sauer, Gold, & Seuring (2021)	South African mining sector, 39 interviews	Single-case study; semi-structured interviews (institutional theory)	Analyze how institutional uncertainty shapes social sustainability in EMDE sourcing	Institutional uncertainty in emerging-market sourcing creates decoupling leeway that weakens realized social sustainability
Huq & Stevenson (2020)	Seven Bangladeshi apparel suppliers	Multiple case study (institutional theory)	Explain implementation and decoupling of socially sustainable practices	Buyer-supported capability building yields more durable compliance than policing; firm-, chain-, and environment-related factors drive decoupling
Kraft, Quayson, & Kellner (2025)	Supplier-evaluation literature and survey	Systematic literature review and survey	Derive supplier-evaluation criteria under mandatory due-diligence acts (LkSG)	Due-diligence statutes reshape supplier-evaluation criteria, foregrounding social and human-rights dimensions
Samal & Jena (2025)	329 Indian supply-chain and logistics managers	Survey; structural equation modeling (institutional theory)	Test the effect of supply-chain due-diligence practices on performance	Due-diligence practices are positively associated with supply-chain performance; trust and organizational culture moderate the relationship

Chapter 3: Analytical Framework and Analytical Expectations

3.1 Analytical Framework

Building on the sLCA stakeholder–subcategory architecture and the Sustainable Livelihoods Approach developed in the theoretical foundation, **Figure 1** presents an analytical framework for a stage-differentiated, policy-augmented screening sLCA of Bangladesh's frozen shrimp export chain. The framework organizes the construction and interpretation of screening outputs; it specifies no causal pathways or causal effects. Three analytical inputs structure the assessment: the six supply-chain stages and their stage–sector mapping, the four core social-risk indicators, and the comparison between 2013 and 2022. The six stages—hatchery and nursery inputs, feed and farm inputs, grow-out farming, harvest and primary handling, processing and freezing, and export logistics—are mapped to agriculture, industry, and services to operationalize stage-level screening where direct worker-level inventories are unavailable. The core indicators—informality, weekly working hours, child labor, and hazardous child work—represent labor-vulnerability dimensions relevant to screening sLCA and are interpreted through the Sustainable Livelihoods Approach as potential constraints on human and financial livelihood assets.

The stage–sector mapping links each stage to the available sectoral indicator vector, and the four normalized indicators are aggregated under equal baseline weights into the Social Hotspot Score (SHS). The SHS is an intermediate screening index: it summarizes relative stage-level vulnerability on a 0–100 scale and provides the basis for the raw hotspot profile, temporal comparison, and indicator-driver decomposition. Export exposure and Policy Response Capacity are then applied as analytical adjustment layers. Export exposure, derived from export value, export quantity, and importer-market concentration in WITS HS 030613 mirror-trade flows, combines with SHS to generate an exposure-weighted hotspot-priority ranking. The Policy Response Capacity Index (PRCI), coded from legal coverage, enforcement capacity, hazardous-work recognition, remediation and social protection, and due-diligence orientation, combines with SHS to generate the governance-adjusted residual-risk classification.

Sector employment shares and working poverty are retained as contextual interpretation variables. They provide macro labor-market context for interpreting differences in SHS, temporal movement, and residual-risk classification, but they are not aggregated into the SHS, export-exposure score, PRCI, or governance-adjusted residual-risk score. Accordingly, **Figure**

1 places these variables outside the central analytical sequence; its arrows denote analytical inputs, score construction, weighting, adjustment, and output generation rather than causal influence. The framework therefore represents a transparent calculation and interpretation architecture for prioritization, rather than a causal model of labor-risk production.

Figure 1 also shows how the five analytical expectations align with the five research questions. AE1 concerns cross-stage variation in raw screened vulnerability; AE2 concerns non-uniform temporal movement; AE3 concerns the indicator composition of that movement; AE4 concerns the prioritization effect of export exposure; and AE5 concerns the persistence and composition of critical residual risk under weak governance response. These expectations are theory-informed interpretive benchmarks. They do not constitute causal hypotheses, null hypotheses, or statistical-significance claims.

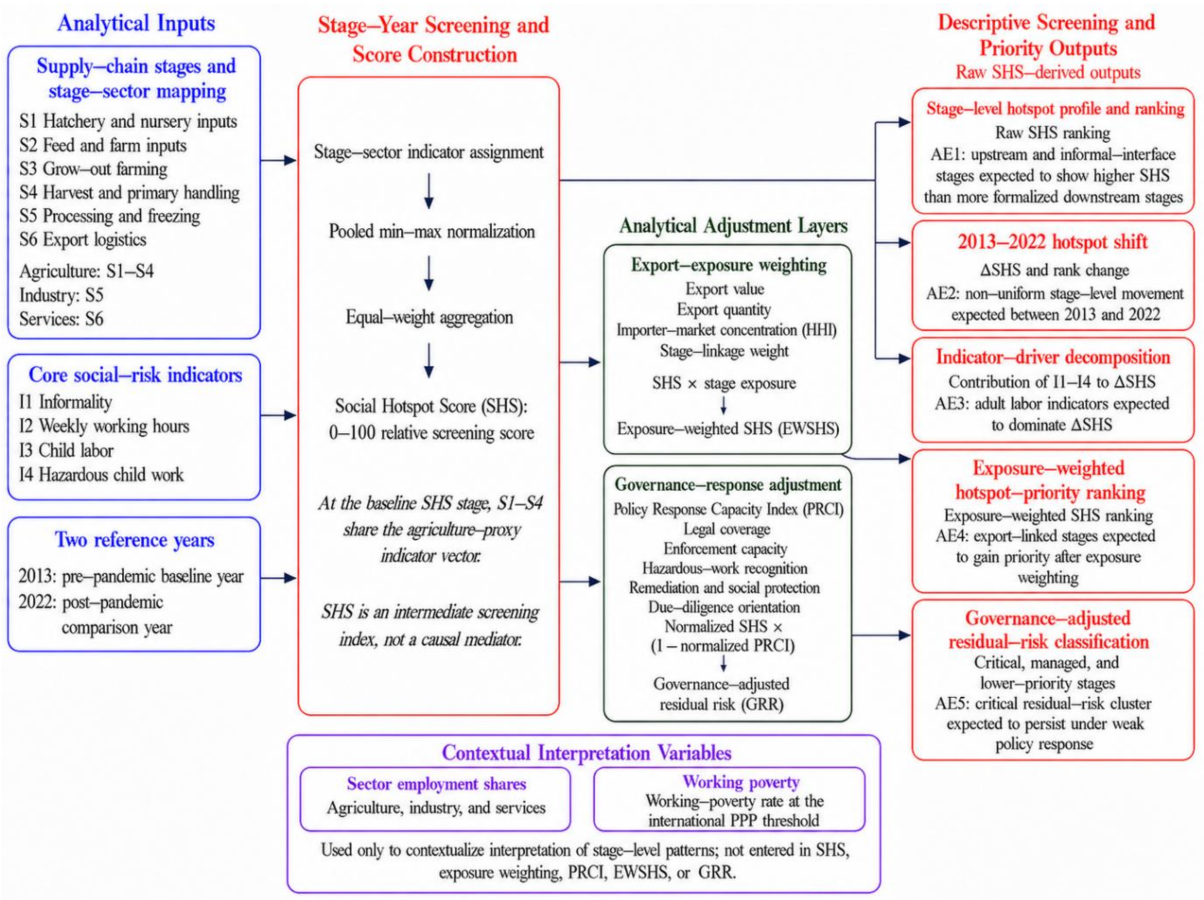

Figure 1. *Analytical framework and analytical expectations for a policy-augmented screening social life cycle assessment of Bangladesh's frozen shrimp export chain*

Note*: AE1–AE5 are theory-informed analytical expectations used to interpret descriptive-comparative screening results; they are not causal hypotheses, null hypotheses, or statistical-significance tests.*

Source: *Authors' own elaboration.*

3.2 Analytical Expectations

Given the descriptive-comparative design of the study, five theory-informed analytical expectations guide interpretation of the findings. They correspond directly to RQ1–RQ5 and specify anticipated descriptive patterns in the stage-level screening results. AE1–AE5 are not causal hypotheses and are not evaluated through null-hypothesis significance testing. Instead, the Results section reports whether the observed descriptive pattern is consistent, partly consistent, or inconsistent with each expectation, while preserving the study's bounded claim that sectoral-proxy scores are relative screening signals rather than verified worker-level conditions.

3.2.1 AE1: Sector-Driven Stage Heterogeneity in Social Hotspots

AE1. Stage-level SHS is expected to differ across the six chain stages, with upstream and informal-interface stages anticipated to display higher screened vulnerability than more formalized downstream stages.

Sectoral proxies inherit the structural labor profile of their parent sector. Agriculture accounted for 45.5 percent of working children aged 5–14 in Bangladesh (International Labour, 2023; Understanding Children's Work, 2011). U.S. Department of Labor (2014, 2023) documents child labor and hazardous work in shrimp-related fishing, drying, and processing activities, alongside forced labor in fish drying. Industry-mapped processing falls partly within enforceable factory and EPZ regimes, which may constrain observable risk where formal inspection reaches. By contrast, stages interfacing with informal labor intermediaries—whether in agricultural collection, primary handling, or services-linked transport and logistics—combine weaker enforcement coverage with sector-specific vulnerability, including high informality in upstream stages and longer working-time exposure in selected downstream service and logistics interfaces. Under additive composite scoring with equal weights, these structural asymmetries provide the basis for anticipating higher screened vulnerability at upstream and informal-interface stages in both observation years.

Stage-specific evidence reinforces this expectation: shrimp collection, pond-side handling, and fish drying recur across USDOL profiles as hazardous and child-labor-prevalent activities, whereas registered processing plants operate under inspection regimes that, however imperfect, may constrain observable risk relative to upstream stages. This expectation concerns relative screening patterns and does not claim verified uniformity or causality at individual worksites.

3.2.2 AE2: Temporal Shift in the Hotspot Profile

AE2. The stage-level SHS profile in 2022 is expected to differ from the 2013 profile through non-uniform movement across stages, rather than through proportional improvement or deterioration at every stage.

Between 2013 and 2022, World Bank WDI data indicate sectoral recomposition: agricultural employment declined from approximately 45.1 to 43.7 percent of total employment, industry declined from 20.8 to 18.0 percent, and services increased from 34.1 to 38.4 percent (World Bank, 2026b). The USDOL country profiles report child work among children aged 5–14 at 10.1 percent in the 2013 profile and 9.2 percent in the 2022 profile, while the share combining work and school increased from 6.8 to 8.2 percent. Because the SHS is responsive to sectoral indicator levels, these movements provide a basis for anticipating non-uniform stage shifts: agriculture-proxy stages may decline more sharply, services-proxy logistics may stagnate or deteriorate relatively, and industry-proxy processing may move with formal-sector labor indicators.

AE2 does not attribute observed change to the COVID-19 pandemic. The contrast is framed as a pre-pandemic baseline and a post-pandemic comparison year, recognizing that pandemic-era school closures, household income shocks, labor-market restructuring, and governance changes may have contributed alongside longer-run structural transformation (Understanding Children's Work, 2011).

3.2.3 AE3: Indicator-Driver Decomposition of the 2013–2022 Shift

AE3. The 2013–2022 changes in stage-level SHS are expected to be driven primarily by adult labor-market structure, especially informality and working-time indicators, rather than by reductions in child-labor-related indicators.

USDOL's downgrade of Bangladesh's assessment from "moderate advancement" in 2013 to "minimal advancement—efforts made but regression in practices that delayed advancement" in 2022 indicates that legal expansion was not matched by proportional enforcement: approximately 400 labor inspectors covered a workforce exceeding 74 million in 2022, and the maximum child-labor fine remained approximately USD 47 (U.S. Department of Labor, 2014, 2023). Headline child-labor incidence moved only modestly, while informality and working-time conditions remained linked to enforcement density, sectoral composition, and labor demand. Under additive decomposition of ΔSHS into informality, weekly working hours, child labor, and hazardous child work, AE3 anticipates that the first two components will make the larger absolute contribution to stage-level change.

The expectation follows composite-index evidence that slow-moving structural indicators can dominate inter-period variance relative to low-base indicators (Saisana & Saltelli, 2011). It does not assume that legal coverage gains automatically reduce SHS, because such gains may not register in screening scores without corresponding changes in formalization, working-time conditions, or observable child-labor indicators.

3.2.4 AE4: Trade-Exposure Reordering of Hotspot Priorities

AE4. Incorporating frozen-shrimp export exposure—export value, export quantity, and importer-market concentration—is expected to alter the stage-priority ranking relative to the raw SHS ranking, with stages directly connected to processing and freezing and export logistics gaining greater policy salience.

Raw SHS captures relative screened vulnerability from sectoral labor proxies, whereas commercial criticality is concentrated unevenly across the chain. Processing and freezing transforms farm-gate output into the HS-coded export commodity tracked in WITS, while export logistics interfaces directly with concentrated buyer markets. Applying normalized export exposure to the SHS elevates stages where moderate screened vulnerability coincides with high commercial throughput, buyer-facing movement, and due-diligence relevance. AE4 therefore anticipates that exposure-weighted ranking will differ from raw SHS ranking, particularly by elevating processing and freezing, harvest and primary handling, and export logistics relative to low-linkage upstream inputs.

This expectation is consistent with responsible-supply-chain due-diligence frameworks that prioritize stages where commercial leverage, audit access, traceability, and remediation capacity are most actionable (OECD and Food and Agriculture Organization of the United Nations, 2016; B. o. I. L. A. U.S. Department of Labor). It does not claim that export exposure causes social risk; exposure weighting provides an ordinal prioritization signal for due-diligence allocation.

3.2.5 AE5: Persistent Critical Residual Risk Under Weak Policy Response

AE5. Stages combining high SHS with weak Policy Response Capacity are expected to remain within a Critical residual-risk category whose size in 2022 is expected to be no smaller than in

2013, given the persistence of governance and enforcement gaps documented in the 2022 USDOL evidence.

The policy augmentation extends the sLCA stakeholder framework—particularly the Value Chain Actors and Society subcategories—by treating governance-response capacity as a stage-relevant adjustment layer in social-risk prioritization, consistent with literature linking due-diligence effectiveness to the institutional environment in producing countries (Macchi & Bright, 2020; Marschke et al., 2021; OECD and Food and Agriculture Organization of the United Nations, 2016). PRCI is coded from legal coverage, enforcement capacity, hazardous-work recognition, remediation and social protection, and due-diligence orientation using USDOL's 2013 and 2022 narratives. Although 2022 recorded legal expansion, persistent gaps in informal-work coverage, EPZ inspection practice, penalty deterrence, and public criminal-enforcement reporting provide a basis for anticipating that weak governance response remains concentrated at stages interfacing with informal labor.

AE5 anticipates that the Critical category—defined by above-median normalized SHS and above-median GRR within each year—will contain at least as many stages in 2022 as in 2013. This is the policy-augmentation core of the framework: a pattern consistent with AE5 would indicate that legislative progress alone has not reduced the size of the Critical residual-risk category and would strengthen the case for inspection density, formalization, remediation access, and buyer-supported due diligence.

Chapter 4: Data and Methodology

4.1 Research Design: Comparative Longitudinal Screening sLCA

The study adopts a comparative longitudinal screening Social Life Cycle Assessment (sLCA) design that compares stage-level social hotspot profiles in Bangladesh's frozen shrimp export chain between two cross-sectional reference years, 2013 and 2022. The design is descriptive-comparative rather than causal-counterfactual: it identifies and ranks stage-level social-risk concentrations using publicly available sectoral labor indicators, bilateral trade-exposure data, and country-level governance evidence, but does not estimate the causal effect of any single shock—including the COVID-19 pandemic—on observed indicator change (Tragnone et al., 2022; United Nations Environment Programme, 2020). The unit of analysis is the stage–year combination, yielding twelve primary observations (six stages × two reference years), each carrying four core indicators, three export-exposure variables, five governance dimensions, and contextual interpretation variables.

This design follows established practice in screening-type Type I sLCA assessments, where stage-level hotspot ranking is prioritized over verified worker-level condition measurement (Benoît Norris et al., 2014; Ramos Huarachi et al., 2020). The four core indicators correspond to SDG 8 sub-targets on labor informality (Target 8.3), working time (Target 8.5), and the eradication of child labor and hazardous child work (Target 8.7), while the governance-augmentation layer connects the framework to SDG 12.6 on responsible production in export-oriented supply chains, anchoring the methodology to the sustainable agri-food supply chain agenda.

The choice of 2013 and 2022 as comparison years reflects three considerations. First, both years are anchored by USDOL Findings on the Worst Forms of Child Labor country profiles, which provide directly comparable qualitative governance evidence (USDOL, 2014, 2023). Second, the interval brackets the COVID-19 pandemic, allowing pre-pandemic baseline and post-pandemic comparison-year framing without authorizing causal attribution (International Labour, 2022; Marschke et al., 2021). Third, 2013 is the earliest year with consistent ILOSTAT and WITS coverage at the disaggregation required for the four core indicators, while 2022 is the most recent year with complete coverage at the time of data extraction. The descriptive-comparative inferential register is preserved across all four estimation models presented in the estimation strategy and the exploratory hierarchical-clustering layer.

4.2 Goal, Scope, and Stage–Sector Mapping

The assessment goal is to identify and compare stage-level social hotspots in Bangladesh's frozen shrimp export chain, classify residual risk under stage-specific governance response, and generate a prioritized policy-intervention map for this agri-food and agro-industrial export commodity (United Nations Environment Programme, 2020). The system boundary is cradle-to-export-gate, beginning at hatchery and nursery inputs and terminating at the export-port handover. The functional unit is 1 kg of frozen shrimps and prawns exported from Bangladesh under HS 030613. Because the assessment uses sectoral proxy indicators rather than stage-specific labor inventories allocated to product mass, the SHS is interpreted as a relative stage-level screening score associated with this reference flow, not as a measured social impact per kilogram. The stage–year combination is the unit of analysis. The chain is decomposed into six analytical stages, indexed S1 through S6: hatchery and nursery inputs (S1); feed and farm inputs (S2); grow-out farming (S3); harvest and primary handling (S4); processing and freezing (S5); and export logistics (S6) (Belton et al., 2017; Paul & Vogl, 2011). **Figure 2** maps these stages within the cradle-to-export-gate system boundary.

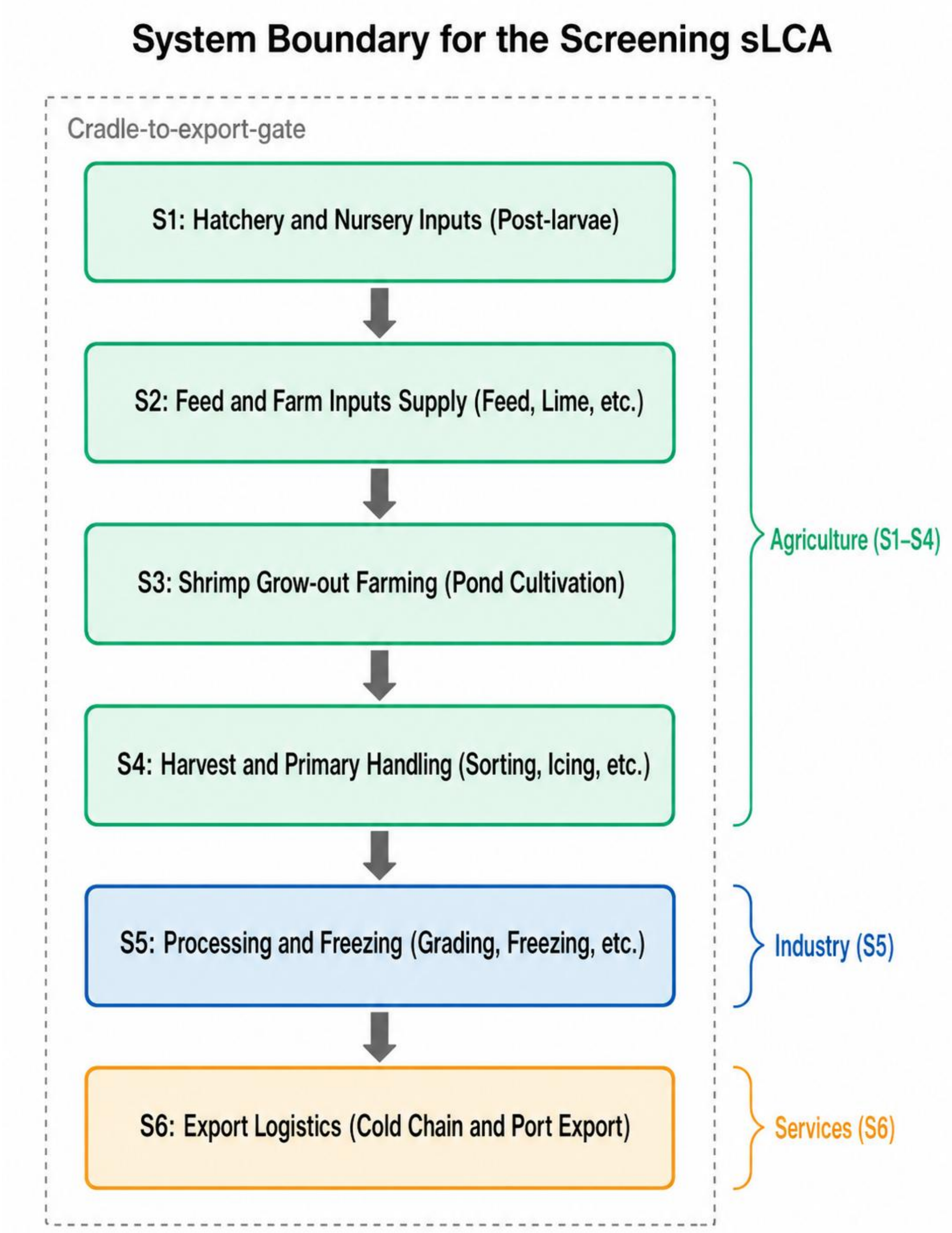

Figure 2. *System boundary for the screening sLCA of Bangladesh's frozen shrimp export chain*

Notes: The boundary is cradle-to-export-gate, spanning six sequential stages from hatchery and nursery inputs (post-larvae) to cold-chain and port-export logistics. The reference commodity is frozen shrimps and prawns under HS 030613. The functional unit is 1 kg of frozen shrimps and prawns exported from Bangladesh under HS

030613. Because the assessment uses sectoral proxy indicators rather than stage-specific labor inventories allocated to product mass, the SHS is interpreted as a relative stage-level screening score associated with this reference flow, not as a measured social impact per kilogram. The stage–year combination is the unit of analysis. Stages are indexed S1–S6 and are grouped by ISIC-aligned sector: agriculture (S1–S4), industry (S5), and services (S6). The band labels and color coding indicate that the four agricultural stages share one sectoral proxy block.

Figure 2 depicts the cradle-to-export-gate boundary as a single downstream sequence, from hatchery and nursery inputs supplying post-larvae, through feed and farm-input supply, grow-out pond cultivation, and harvest and primary handling, to processing and freezing and, finally, cold-chain and port-export logistics. This boundary is deliberately wider than the cradle-to-farm-gate scope that predominates in shrimp and prawn life-cycle studies, where assessments commonly terminate at the pond gate and exclude processing, freezing, and export movement (Pazmiño, Chico-Santamarta, Boero, & Ramirez, 2024; Ruiz-Salmón et al., 2021). The extension is analytically necessary because the screened social-risk concentrations are distributed across the post-harvest handling, processing, and logistics interfaces that a farm-gate boundary would omit, and because these downstream stages carry the commercial transformation and cold-chain movement that connect Bangladeshi production to concentrated import markets (Belton et al., 2017; Mahmud et al., 2026). The single-direction process flow additionally fixes the upstream-to-downstream ordering applied in the stage-linkage exposure weights of the exposure-weighting model, so that the depicted chain and the exposure-weighting pipeline reference an identical stage sequence.

Each stage is mapped to one of three ISIC-aligned economic activities—agriculture, industry, or services—to operationalize sectoral proxy assignment where shrimp-specific worker-level inventory data are unavailable (Sureau et al., 2018; Wu et al., 2014). Stages S1–S4 (hatchery, feed input, grow-out, and harvest) are mapped to agriculture; S5 (processing and freezing) is mapped to industry; and S6 (export logistics) is mapped to services. The mapping yields a stage–sector key that governs the merge between supply-chain stages and ILOSTAT sectoral indicators throughout the analytical pipeline.

Because the four upstream stages (S1–S4) share the agricultural proxy, they carry identical sectoral indicator values and therefore an identical baseline Social Hotspot Score. This identity is a deliberate property of the stage-differentiated screening design, not a substantive claim of uniform social conditions: the agricultural stages are separated only downstream, and only to the extent that their stage-linkage exposure weights (**Table 5**) and stage-specific Policy Response Capacity Index coding differ. Where more than one economic activity could plausibly apply to a stage, the dominant labor-relations regime is assigned on conceptual and operational grounds. This mapping is treated as a transparent modeling assumption and is not subjected to a separate stage-sector remapping sensitivity analysis.

4.3 Research Variables, Sources, and Proxies

Table 3 documents the analytical variables, their empirical proxies, source databases, survey or indicator codes, and the corresponding file names from the analytical workspace. The measurement strategy is deliberately parsimonious: each construct is anchored in directly observable indicators from international statistical authorities (ILOSTAT, World Bank WDI, WITS) and government documentary sources (USDOL), preserving conceptual fit between constructs and proxies. The four core indicators that enter the Social Hotspot Score—informality (I1), weekly working hours (I2), child labor (I3), and hazardous child work (I4)—are sourced from harmonized ILOSTAT bulk files at sex- and economic-activity-disaggregated levels, with age detail for the hours and child-labor files (International Labour Organization, 2026).

Export-exposure variables (export value V, export quantity Q, and the Herfindahl–Hirschman Index of importer concentration HHI) are derived from WITS HS 030613 (frozen shrimps and prawns) mirror-import trade flows (World Bank, 2026c). Sector employment shares (EMP_AGR, EMP_IND, EMP_SRV) are retained as contextual interpretation variables for interpreting sectoral labor-market structure and are extracted from the World Bank WDI series (World Bank, 2026a). Governance evidence for the Policy Response Capacity Index is coded from the USDOL country profiles for the 2013 and 2022 reporting years (U.S. Department of Labor, 2014, 2023).

Table 3. Research variables, source modules, survey codes, and analytical file names

Variable block	Code	Proxy used in analysis	Indicator Source/Module	Survey item/Code	File name
Core social-risk indicator: Informality	I1	Share of informal employment in total employment by economic activity (%)	ILOSTAT SDG 8.3.1 module	SDG_0831_SEX_ECO_RT	SDG_0831_SEX_ECO_RT_A-20260307T0749.csv

Variable block	Code	Proxy used in analysis	Indicator Source/Module	Survey item/Code	File name
Core social-risk indicator: Weekly working time	I2	Mean weekly hours actually worked per employed person by economic activity	ILOSTAT Hours-of-work module	HOW_TEMP_SEX_AGE_ECO_NB	HOW_TEMP_SEX_AGE_ECO_NB_A-20260307T0747.csv
Core social-risk indicator: Child labor	I3	Children in employment by economic activity, converted to normalized risk score	ILOSTAT Child-labor module	CLD_XCHL_SEX_AGE_ECO_NB	CLD_XCHL_SEX_AGE_ECO_NB_A-20260307T0750.csv
Core social-risk indicator: Hazardous child work	I4	Children in hazardous work by economic activity, converted to normalized risk score	ILOSTAT Hazardous-child-work module	CLD_XHAZ_SEX_AGE_ECO_NB	CLD_XHAZ_SEX_AGE_ECO_NB_A-20260307T0751.csv
Export exposure	V, Q, HHI	Export value (USD), export quantity (kg), and Herfindahl–Hirschman Index of importer concentration	WITS HS 030613 mirror trade flows	HS 030613 (frozen shrimps and prawns)	WITS-By-HS6Product_2013.xlsx; WITS-By-HS6Product_2022.xlsx
Sector employment context	EMP_AGR	Employment in agriculture (% of total employment)	World Bank WDI	SL.AGR.EMPL.ZS	API_SL.AGR.EMPL.ZS_DS2_en_csv_v2_692.csv
Sector employment context	EMP_IND	Employment in industry (% of total employment)	World Bank WDI	SL.IND.EMPL.ZS	API_SL.IND.EMPL.ZS_DS2_en_csv_v2_5015.csv
Sector employment context	EMP_SRV	Employment in services (% of total employment)	World Bank WDI	SL.SRV.EMPL.ZS	API_SL.SRV.EMPL.ZS_DS2_en_csv_v2_4736.csv

Variable block	Code	Proxy used in analysis	Indicator Source/Module	Survey item/Code	File name
Working-poverty context	WP	Working-poverty rate at the international PPP threshold (%)	ILOSTAT SDG 1.1.1 module	SDG_0111_SEX_AGE_RT	SDG_0111_SEX_AGE_RT_A-20260307T0753.csv
Governance evidence (PRCI inputs)	P1–P5	Legal coverage; enforcement capacity; hazardous-work recognition; remediation and social protection; due-diligence orientation	USDOL Findings on the Worst Forms of Child Labor (country profiles)	Country profile narrative coding	Bangladesh__2013_Findings_on_the_Worst_Forms_of_Child_Labor.pdf; Bangladesh__2022_Findings_on_the_Worst_Forms_of_Child_Labor.pdf

Note: Indicator files were extracted from the ILOSTAT bulk download facility (International Labour Organization, 2026), World Bank WDI sector-employment extracts and associated metadata (World Bank, 2026a), and the WITS mirror-trade database (World Bank, 2026c); governance evidence was coded from the USDOL Bangladesh country profiles (U.S. Department of Labor, 2014, 2023).

The measurement architecture distinguishes four analytical roles. Core indicators (I1–I4) enter the additive composite SHS directly and inform interpretation of the patterns specified in AE1–AE3. Export-exposure variables (V, Q, HHI) scale the SHS into an exposure-weighted ranking used to examine the prioritization pattern specified in AE4, while governance dimensions (P1–P5) form the PRCI used in the governance-adjusted residual-risk classification considered in AE5. Contextual variables—working poverty and sector employment shares—support interpretation but are not aggregated into the primary composite. This stratification preserves analytical transparency and prevents conceptual slippage between the four primary worker-subcategory constructs and a wider set of macro labor-market indicators that influence interpretation but should not contaminate the composite score (Nardo et al., 2008; Saisana & Saltelli, 2011). Six ILOSTAT files (two occupational-injury files; four labor-inspection files) were screened during data triage and excluded from the main model because they did not provide Bangladesh-disaggregated rows for both reference years; their exclusion is logged in the supplementary reproducibility protocol.

4.4 Variables and Theoretical Justification

Table 4 links each empirical variable to its theoretical anchor and explains why the variable enters the analytical model in its present role. Variable selection follows the integrated theoretical grounding developed in **Section 2**: the four core indicators correspond to the worker subcategory of the UNEP sLCA Guidelines (United Nations Environment Programme, 2020) and to the human- and financial-capital dimensions of the Sustainable Livelihoods Approach (Natarajan et al., 2022; Scoones, 2009); export-exposure variables operationalize the activity-variable weighting tradition in conventional sLCA characterization (Benoît Norris et al., 2014); governance dimensions operationalize the OECD-FAO due-diligence cycle as a stage-relevant policy-response capacity layer (Macchi & Bright, 2020; OECD and Food and Agriculture Organization of the United Nations, 2016); and contextual variables provide the macro labor-market backdrop against which stage-level results are interpreted, without entering the composite score itself.

Table 4. Variables, empirical proxies, theoretical anchors, and theoretical justification

Variable block	Code	File name	Empirical proxy	Theoretical anchor	Theoretical justification
Core social-risk indicators	I1–I4	SDG_0831_SEX_ECO_RT...csv; HOW_TEMP_SEX_AGE_ECO_NB...csv; CLD_XCHL_SEX_AGE_ECO_NB...csv; CLD_XHAZ_SEX_AGE_ECO_NB...csv	Informality (I1), weekly working hours (I2), child labor (I3), hazardous child work (I4) by economic activity	UNEP sLCA Guidelines; Sustainable Livelihoods Approach	Operationalize the Worker subcategory of the sLCA stakeholder architecture (Benoit-Norris et al., 2014; UNEP, 2020) and the human- and financial-capital dimensions of the SLA capitals framework (Scoones, 2009; Natarajan et al., 2022); capture the labor-vulnerability dimensions most relevant to a screening composite where stage-specific worker-level data are unavailable.
Export-exposure variables	V, Q, HHI	WITS-By-HS6Product_2013.xl	Export value, export quantity, and importer-	Activity-variable weighting	Operationalize the activity-variable scaling logic that

Variable block	Code	File name	Empirical proxy	Theoretical anchor	Theoretical justification
		sx; WITS-By-HS6Product_2022.xlsx	market concentration (HHI)	tradition in conventional sLCA characterization	converts per-worker screened risk into commercially weighted risk salience (Benoit-Norris et al., 2014); identifies stages where moderate per-worker vulnerability coincides with high commercial throughput and provides the trade-salience comparison examined in AE4.
Sector employment context	EMP_AGR, EMP_IND, EMP_SRV	API_SL.AGR.EMPL.ZS...csv; API_SL.IND.EMPL.ZS...csv; API_SL.SRV.EMPL.ZS...csv	Sectoral employment shares (agriculture, industry, services)	Sectoral structural-transformation literature	Provide the macro labor-market backdrop for interpreting stage-level SHS movements (World Bank, 2026a); capture sectoral recomposition relevant to the non-uniform temporal patterns examined in AE2.
Working-poverty context	WP	SDG_0111_SEX_AGE_RT...csv	SDG 1.1.1 working-poverty rate	SLA financial-capital dimension; sustainable-livelihoods diagnostic	Connects labor-market indicators to household financial vulnerability (Scoones, 2009; Natarajan et al., 2022), supporting interpretive integration between worker-level and household-level scales without entering the composite SHS.
Governance evidence (PRCI inputs)	P1–P5	Bangladesh__2013_Findings_on_the_Worst_Forms_o	Legal coverage, enforcement capacity, hazardous-work	OECD-FAO due-diligence cycle; stage-	Operationalize stage-relevant policy-response capacity within the governance-adjusted

Variable block	Code	File name	Empirical proxy	Theoretical anchor	Theoretical justification
		f_Child_Labor.pdf; Bangladesh__2022_Findings_on_the_Worst_Forms_of_Child_Labor.pdf	recognition, remediation and social protection, due-diligence orientation	relevant policy-response capacity framing	residual-risk classification (OECD-FAO, 2016; Macchi & Bright, 2020) by pairing screened vulnerability with stage-relevant governance-response capacity under AE5.

This theory-led variable selection serves two methodological functions. First, it disciplines the screening composite against the criticism that proxy-based scoring is purely data-driven; each component of the SHS, exposure weighting, and PRCI carries an explicit theoretical commitment that can be cross-examined against the chosen proxy. Second, it preserves the descriptive-comparative inferential register of the study: variables are selected to populate a screening and prioritization model, not to identify causal pathways. The Bayesian-network or structural-equation framing that would be necessary for causal decomposition is intentionally not invoked, consistent with the screening sLCA tradition's emphasis on relative-risk signaling over verified condition estimation (Díez-Hernández et al., 2026; Tragnone et al., 2022). Contextual variables are retained to support interpretation of stage-level patterns without entering the core composite or implying causal control.

4.5 Estimation Strategies

The estimation architecture proceeds through four linked analytical models, each addressing a descriptive analytical task and an associated analytical expectation within the screening-and-policy-augmentation logic. Each model is presented in closed form below, with equation numbering preserved for cross-reference in the Results and Discussion Section. All models are estimated separately for 2013 and 2022 to support delta and rank-shift comparison. Numerical estimation is implemented using Python 3.11 (composite-score construction, decomposition, PRCI coding, hierarchical clustering, and silhouette diagnostics), with all reproducibility logs maintained per the protocol in the reproducibility protocol Section.

4.5.1 Min-Max Normalized Social Hotspot Score

Each core indicator is normalized to a 0–100 interval using a temporal min–max transformation that pools across both observation years **(Equation 1)**:

$$x_{i,s,t}^{\text{norm}} = \frac{x_{i,s,t} - \min_{s,t}(x_i)}{\max_{s,t}(x_i) - \min_{s,t}(x_i)} \times 100 \quad (1)$$

where $x_{i,s,t}$ is the raw value of indicator i for stage s in year t, and the minimum and maximum are taken across the full stage–year grid for indicator i. Pooled min–max normalization preserves cross-year comparability so that ΔSHS values in **Equation 4** carry meaningful directional information rather than reflecting period-specific rescaling artifacts (Greco et al., 2019). The stage–year Social Hotspot Score is then constructed under equal weights **(Equation 2)**:

$$\text{SHS}_{s,t} = \sum_{i=1}^{4} w_i \cdot x_{i,s,t}^{\text{norm}}, \quad w_i = 0.25, \quad \sum_{i} w_i = 1 \quad (2)$$

Equal weighting is the defensible default for screening composites where expert weight elicitation is infeasible (Becker et al., 2017). A general weighted form is retained for the sensitivity tests in the robustness analysis Section **(Equation 3)**:

$$\text{SHS}_{s,t}^{(w)} = \sum_{i=1}^{4} w_i \cdot x_{i,s,t}^{\text{norm}}, \quad \sum_{i=1}^{4} w_i = 1 \quad (3)$$

4.5.2 Temporal Delta and Indicator-Driver Decomposition

The temporal delta for each stage captures the directional change in screened social vulnerability between the two reference years **(Equation 4)**:

$$\Delta\text{SHS}_s = \text{SHS}_{s,2022} - \text{SHS}_{s,2013} \quad (4)$$

Positive values indicate increased screened vulnerability between 2013 and 2022; negative values indicate reduction. Because the SHS is linear-additive in the normalized indicators, the delta admits an exact additive decomposition into indicator-level contributions **(Equation 5)**:

$$\Delta\text{SHS}_s = \sum_{i=1}^{4} w_i \cdot \left(x_{i,s,2022}^{\text{norm}} - x_{i,s,2013}^{\text{norm}}\right) = \sum_{i=1}^{4} c_{i,s} \quad (5)$$

where $c_{i,s}$ is indicator i's additive contribution to stage s's temporal shift. This decomposition is used to examine AE3: the expected pattern would be observed if informality (I1) and weekly hours (I2) made larger absolute contributions to stage-level change than child labor (I3) and hazardous child work (I4). The decomposition outputs feed directly into the indicator-driver table reported in **Table 10**.

4.5.3 Export-Exposure-Weighted Hotspot Prioritization

Export-exposure weighting distinguishes raw social vulnerability from commercially salient social vulnerability. Because WITS HS 030613 mirror trade flows are observed at the exported-commodity level rather than separately for each supply-chain stage, export exposure is first calculated at the commodity-year level and then allocated to stages through a transparent stage-linkage weight. This specification avoids falsely implying that WITS directly observes stage-specific export value or quantity. The commodity-level export exposure score is **(Equation 6)**:

$$E_t = \frac{1}{3}(V_t^* + Q_t^* + HHI_t^*) \quad (6)$$

where V_t^*, Q_t^*, and HHI_t^* are normalized export value, export quantity, and importer-market concentration for year t. The Herfindahl–Hirschman Index is calculated as **(Equation 7)**:

$$HHI_t = 10{,}000 \times \sum_{m=1}^{M} share_{m,t}^2 \quad (7)$$

where $share_{m,t}$ is importer m's share of Bangladesh's HS 030613 mirror-import value in year t. Stage exposure is then defined as **(Equation 8)**:

$$SE_{s,t} = L_s \times E_t \quad (8)$$

where L_s is the stage-linkage weight that captures how directly each stage is connected to the export transaction. Processing/freezing and export logistics receive the strongest export linkage because they transform, preserve, certify, and move the HS-coded export commodity. Harvest and primary handling receive intermediate linkage because they connect farm output to export-processing channels. Hatchery, nursery, feed-input, and grow-out stages receive lower but non-zero linkage because they supply the biological production base of the exported commodity. This stage-linkage structure is consistent with Life Cycle Thinking because it preserves upstream-to-downstream responsibility rather than treating the export node as socially isolated from the production chain (Benoît Norris et al., 2014; United Nations Environment Programme, 2020).

The baseline stage-linkage weights are reported in **Table 5**. These weights are not treated as observed trade data; they are methodological allocation assumptions used to connect commodity-level export exposure with stage-level hotspot scores. The exposure-weighted Social Hotspot Score is calculated as **(Equation 9)**:

$$EWSHS_{s,t} = SHS_{s,t} \times SE_{s,t} \ (9)$$

Table 5. Baseline stage-linkage weights for exposure-weighted hotspot prioritization

Stage	Baseline ($\boldsymbol{L_s}$)	Rationale
S1: Hatchery and nursery inputs	0.50	Indirect but necessary biological input to the exported commodity
S2: Feed and farm inputs	0.50	Indirect input-stage exposure
S3: Grow-out farming	0.60	Direct production base but not the export transaction node
S4: Harvest and primary handling	0.75	Interface between production and export-processing chain
S5: Processing and freezing	1.00	Direct HS-coded export transformation stage
S6: Export logistics	1.00	Direct export movement and buyer-facing stage

This model does not claim that export exposure causes social risk. It identifies whether a socially vulnerable stage is also commercially salient for export-chain due diligence, buyer monitoring, and policy prioritization. The stage-linkage weights are transparent allocation assumptions, so the exposure-weighted scores should be interpreted as comparative prioritization signals rather than as direct measures of stage-specific trade exposure. This interpretation aligns with responsible agricultural supply-chain due diligence, in which risk identification and prioritization extend across the supply chain rather than remain limited to a single formal processing node (OECD and Food and Agriculture Organization of the United Nations, 2016).

4.5.4 Policy Response Capacity Index and Governance-Adjusted Residual-Risk Matrix

The Policy Response Capacity Index is coded at the stage-year level because governance capacity is not uniform across the shrimp export chain. Legal coverage, inspection reach, hazardous-work recognition, remediation access, and due-diligence orientation differ across small farms, informal handling, processing plants, and logistics interfaces. The 2013 USDOL report documents child labor in agriculture and services, including coastal shrimp and dried-fish activities, and notes that children in the informal sector lacked adequate protection. The

2022 USDOL report similarly identifies hazardous child work in fishing, drying, and processing fish including shrimp, while also recording continuing gaps in legal coverage, inspection capacity, penalties, referral systems, and informal-sector protection. These differences justify a stage-specific PRCI rather than a single national-year governance score.

Each stage $s$in year $t$is scored across five governance dimensions: legal coverage ($P1$), enforcement capacity ($P2$), hazardous-work recognition ($P3$), remediation and social protection ($P4$), and due-diligence orientation ($P5$). Each dimension is coded on a three-point ordinal scale: 1 = weak capacity, 2 = partial capacity, and 3 = stronger capacity. The coding rubric is reported in **Table 6**.

Table 6. PRCI coding rubric for stage-year governance-response capacity

PRCI dimension	Score = 1 (weak capacity)	Score = 2 (partial capacity)	Score = 3 (stronger capacity)
Legal coverage	Stage largely outside labor-law protection or covered only indirectly	Partial legal coverage with gaps for informal, small-scale, or subcontracted work	Clear legal coverage and enforceable standards
Enforcement capacity	Weak inspection reach, low penalties, or no stage-relevant enforcement evidence	Some inspection or enforcement evidence, but limited reach	Regular stage-relevant enforcement with meaningful sanctions
Hazardous-work recognition	Hazardous tasks not clearly recognized for the stage	Related hazardous activities recognized, but stage coverage incomplete	Stage-relevant hazardous work clearly recognized
Remediation/social protection	No clear referral, rehabilitation, education, or social-protection pathway	Some programs exist, but limited stage reach	Clear remediation and protection mechanisms relevant to the stage
Due-diligence orientation	Weak traceability, weak buyer leverage, or weak monitoring relevance	Partial monitoring or buyer leverage	Strong monitoring, traceability, or buyer-facing due-diligence relevance

The PRCI is calculated after converting the 1–3 ordinal coding scale into a zero-based governance-capacity score. For each dimension, the weak-capacity score is treated as the lower bound, so $p_{k,s,t} = 1$ maps to 0, $p_{k,s,t} = 2$ maps to 0.5, and $p_{k,s,t} = 3$ maps to 1. The stage-year PRCI is therefore calculated as **(Equation 10)**:

$$PRCI_{s,t} = 100 \times \frac{\sum_{k=1}^{5} \omega_k \left(\frac{p_{k,s,t} - 1}{2}\right)}{\sum_{k=1}^{5} \omega_k} \quad (10)$$

where $p_{k,s,t} \in [1,2,3]$ is the coded governance score for dimension k, stage s, and year t, and ω_k is the dimension weight. The baseline specification uses equal weights ($\omega_k = 1$). The transformation $(p_{k,s,t} - 1)/2$ rescales the 1–3 ordinal rubric to a 0–1 interval before aggregation, so the weakest possible governance-response profile receives a PRCI of 0 and the strongest possible profile receives a PRCI of 100. Equal weighting is used for the same reason as the SHS baseline: no validated expert-elicited weight set exists for Bangladesh's shrimp-chain governance capacity, so transparent equal weighting is preferable to arbitrary differential weighting, provided sensitivity checks are reported (Becker et al., 2017; Saisana & Saltelli, 2011).

For the residual-risk calculation, $PRCI^*_{s,t}$ is obtained by dividing $PRCI_{s,t}$ by 100. The governance-adjusted residual-risk score combines normalized SHS and normalized PRCI in inverse-multiplicative form **(Equation 11)**:

$$GRR_{s,t} = SHS^*_{s,t} \times \left(1 - PRCI^*_{s,t}\right) \quad (11)$$

where $SHS^*_{s,t}$ and $PRCI^*_{s,t}$ are rescaled to the 0–1 interval. Higher $GRR_{s,t}$ indicates a stage that combines high screened social vulnerability with weak governance-response capacity. This specification is consistent with the policy-response literature because social-risk identification alone is insufficient; enforcement density, legal coverage, remediation mechanisms, and due-diligence capacity shape whether identified risk can translate into corrective action (Decker Sparks et al., 2022; Macchi & Bright, 2020; Marschke et al., 2021; OECD and Food and Agriculture Organization of the United Nations, 2016).

Residual-risk categories are assigned using a within-year median-split rule **(Equation 12)**:

$$Category_{s,t} = \begin{cases} Critical, & SHS^*_{s,t} \geq Median(SHS^*_t) \text{ and } GRR_{s,t} \geq Median(GRR_t) \\ Managed, & SHS^*_{s,t} \geq Median(SHS^*_t) \text{ and } GRR_{s,t} < Median(GRR_t) \\ Latent, & SHS^*_{s,t} < Median(SHS^*_t) \text{ and } GRR_{s,t} \geq Median(GRR_t) \\ Lower\ priority, & SHS^*_{s,t} < Median(SHS^*_t) \text{ and } GRR_{s,t} < Median(GRR_t) \end{cases} \quad (12)$$

This specification treats normalized SHS as inherent screened vulnerability and GRR as residual vulnerability after governance adjustment. Critical stages are above the within-year medians of both SHS and GRR; Managed stages have above-median SHS but below-median GRR; Latent stages have below-median SHS but above-median GRR; and Lower-priority stages are below both medians. Because GRR incorporates PRCI inversely, the classification retains the governance-response logic while distinguishing inherent vulnerability from residual risk. The categories are descriptive screening classifications rather than causal estimates. Because four agriculture-proxied stages tie at the 2022 SHS median, the 2022 classification is governed effectively by GRR alone, and the Latent cell is unpopulated in both observation years.

4.6 Exploratory Hierarchical-Clustering Analysis

Hierarchical agglomerative clustering is used as an exploratory pattern-analysis layer rather than as a predictive or validation model. The analytical dataset contains twelve primary stage-year observations and no externally observed outcome variable; supervised methods such as random forest, XGBoost, and neural networks are therefore unsuitable. Ward clustering groups stage-year observations by similarity across normalized hotspot, exposure, governance-capacity, and residual-risk features without estimating an outcome model (James, Witten, Hastie, & Tibshirani, 2021; Murtagh & Legendre, 2014). Because the clustering inputs include SHS, PRCI, and GRR-related features that are analytically connected, the clustering solution is not treated as an independent test of the governance-adjusted residual-risk classification. Instead, it is used to identify broad structural patterns and mixed stage-year profiles within the multidimensional screening dataset. Ward's criterion is appropriate because it minimizes within-cluster variance during agglomerative merging (Murtagh & Legendre, 2014).

The clustering input vector is specified as **(Equation 13)**:

$$\boldsymbol{v}_{s,t} = \left[SHS^*_{s,t}, EWSHS^*_{s,t}, PRCI^*_{s,t}, RRR_{s,t}\right] \quad (13)$$

where $SHS^*_{s,t}$, $EWSHS^*_{s,t}$, and $PRCI^*_{s,t}$ are normalized to the 0–1 interval, and $RRR_{s,t}$ is the governance-adjusted residual-risk score. Ward's minimum-variance linkage is used **(Equation 14)**:

$$D(A,B) = \frac{|A||B|}{|A|+|B|} \| \bar{\boldsymbol{v}}_A - \bar{\boldsymbol{v}}_B \|^2 \quad (14)$$

where A and B are candidate clusters and $\bar{\mathbf{v}}$ is the cluster centroid. Average silhouette width is used to assess the internal separation of candidate clustering solutions by comparing each observation's cohesion within its assigned cluster with its separation from neighboring clusters (Rousseeuw, 1987). The silhouette statistic is interpreted as an internal separation diagnostic rather than external validation of the residual-risk categories.

The clustering output is interpreted as an exploratory structural diagnostic. It identifies stage-year profiles that share similar combinations of screened vulnerability, export-exposure salience, governance-response capacity, and residual risk. Any correspondence or difference between Ward-cluster membership and the median-split residual-risk categories is reported descriptively as an indication of alignment or mixed profiles, not as evidence that clustering validates or invalidates those categories. The cluster output is presented alongside the ranking-stability checks in **Table 13** but does not constitute a competing main model. The dendrogram and clustered heatmap are reported as visual diagnostics of the clustering solution.

4.7 Robustness and Sensitivity Analysis

Robustness analysis evaluates whether stage-level hotspot rankings remain stable under the sensitivity specifications reported in **Table 13**. The first check re-estimates the Social Hotspot Score under three weighting schemes: equal weights, adult-labor-dominant weights, and child-risk-dominant weights. This test addresses the standard composite-index concern that equal weighting may impose an arbitrary importance structure across indicators (Becker et al., 2017; Saisana & Saltelli, 2011). The second check excludes the two child-risk indicators—child labor and hazardous child work—and recalculates the SHS from informality and weekly working hours. This test examines whether the ranking depends primarily on child-risk indicators rather than on the broader labor-risk profile (Greco et al., 2019).

The ranking-stability assessment compares the baseline SHS ranking with rankings generated by the alternative-weighting and child-risk-excluded specifications. Ward hierarchical clustering is reported separately as an exploratory pattern-analysis layer that profiles stage-year observations across hotspot, exposure, governance-capacity, and residual-risk features. It is not treated as a sensitivity test or as an independent validation procedure. All robustness and clustering results are reported descriptively without statistical-significance claims.

4.8 Reproducibility, Limitations, and Data-Quality Protocol

All analytical scripts, source files, extraction rules, and transformation decisions were retained in a reproducibility archive. Six ILOSTAT files were archived as non-usable for the main model: two occupational-injury files (INJ_FATL, INJ_NFTL) lacked Bangladesh coverage for both reference years, and four labor-inspection files (LAI_INSP, LAI_VIST, LAI_INDE, LAI_VDIN) did not contain Bangladesh-disaggregated rows (International Labour, 2026). A vulnerable-employment series (SL.EMP.VULN.ZS) was downloaded during data assembly but not retained in the analytical model. Three structural limitations are explicitly acknowledged: sectoral proxies cannot verify firm-level conditions; some indicators are contextual rather than stage-specific; and observed 2013–2022 differences are descriptive—they are not causal COVID-effect estimates. The PRCI coding rubric, indicator-weighting specifications, stage-linkage allocation assumptions, and Ward clustering settings are documented in the methodology and retained in the analytical archive.

Chapter 5: Results

Table 7 reports the descriptive social-risk profile and chain-level context for 2013 and 2022. Informality remains high across all sector proxies but declines, most markedly in services (77.3% to 67.1%) and least in agriculture, where it stays near-universal (97.7% to 96.5%). Mean weekly hours diverge by sector, falling in agriculture (41.9 to 37.0) while rising in industry (48.6 to 52.2). Both child-related indicators contract in every sector, with the steepest decline in agricultural hazardous child work (686.1 to 254.1 thousand). At the chain level, frozen-shrimp export value falls from USD 491.4 to 346.0 million and export quantity from 48.8 to 27.2 million kilograms, while importer concentration rises (HHI 1,090 to 1,314), indicating a contracting export base served through a more concentrated buyer market. Working poverty declines from 19.1% to 7.0%, and sectoral employment shares move toward services (34.1% to 38.4%) and away from agriculture (45.1% to 43.7%) and industry (20.8% to 18.0%).

The employment-share movement recorded in **Table 7** marks a sectoral recomposition toward services-linked work across the observation window. This recomposition is the macro labor-market backdrop against which the stage-level hotspot movements are interpreted, and it motivates the non-uniform temporal change examined in the delta and decomposition tables. It is presented as descriptive context for the stage-level patterns and not as a causal driver of the screened indicator levels, consistent with the non-causal positioning of the study design.

Table 7. Descriptive sectoral social-risk profile and chain-level context, 2013 and 2022

Year	Sector proxy	I1 Informality (%)	I2 Weekly hours	I3 Child labor (thousands)	I4 Hazardous child work (thousands)	Employment share (%)	Export value (USD mn)	Export quantity (kg mn)	Importer HHI	Working poverty (%)
2013	Agriculture	97.7	41.9	1008.3	686.1	45.1	491.4	48.8	1090	19.1
2013	Industry	90.8	48.6	967.3	752.5	20.8				
2013	Services	77.3	47.9	841.8	552.1	34.1				

Year	Sector proxy	I1 Informality (%)	I2 Weekly hours	I3 Child labor (thousands)	I4 Hazardous child work (thousands)	Employment share (%)	Export value (USD mn)	Export quantity (kg mn)	Importer HHI	Working poverty (%)
2022	Agriculture	96.5	37	858	254.1	43.7				
2022	Industry	90.6	52.2	677.1	490.1	18	346	27.2	1314	7
2022	Services	67.1	49.8	835	533	38.4				

Note: One descriptive table at the sector-year unit. Sector-level social indicators (I1-I4, employment share) are sourced from ILOSTAT and World Bank WDI and broadcast to stages via the stage-sector key. The chain-level context columns (export value, export quantity, importer HHI, working poverty) are economy/commodity-wide and constant within a year; they are merged across each year's three sector rows to indicate they are not sector-specific. Export value, quantity, and HHI are from WITS HS 030613 mirror imports after removing the EU-aggregate reporter.

Table 8 presents the baseline Social Hotspot Scores and within-year rankings **(Eq. 1–2)**. Processing and freezing (S5) records the highest screened vulnerability in both years (85.27 in 2013; 56.00 in 2022), holding rank 1 throughout, a stage-differentiated hotspot pattern consistent with the screening sLCA objective of locating social risk along the product life cycle rather than at a single production node. The four agriculture-proxied stages (S1–S4) share an identical baseline score by construction (79.76 in 2013; 37.68 in 2022), because the stage–sector mapping assigns them a common agriculture indicator vector; they are differentiated only at the exposure and governance layers reported in **Table 11** and **Table 12**. Export logistics (S6) is the lowest-ranked stage in 2013 (53.57, rank 6) and rises to rank 2 in 2022 (46.88). The observed pattern is partly consistent with AE1: stage-level heterogeneity is clear, but processing and freezing, rather than an upstream or informal-interface stage, records the highest raw SHS.

Table 8. Baseline Social Hotspot Scores by stage and year

stage_id	Stage	Sector proxy	SHS_2013	Rank_2013	SHS_2022	Rank_2022
S5	Processing and freezing	Industry	85.27	1	56	1
S6	Export logistics	Services	53.57	6	46.88	2
S1	Hatchery and nursery inputs	Agriculture	79.76	2	37.68	3

stage_id	Stage	Sector proxy	SHS_2013	Rank_2013	SHS_2022	Rank_2022
S2	Feed and farm inputs	Agriculture	79.76	2	37.68	3
S4	Harvest and primary handling	Agriculture	79.76	2	37.68	3
S3	Grow-out farming	Agriculture	79.76	2	37.68	3

*Note: Equal-weight additive SHS on pooled min-max normalized indicators **(Eq.1-2)**. Rank 1 = highest risk.*

Table 9 reports the 2013–2022 hotspot delta and rank shift **(Eq. 4)**. All six stages register a decline in screened vulnerability, but the magnitudes are markedly non-uniform: the agriculture-proxied stages the agriculture-proxied stages decline most steeply, by 42.08 points, processing and freezing declines by 29.27 points, and export logistics declines least, by 6.69 points. The differential decline reorders the ranking, with export logistics rising four positions (rank 6 to rank 2) as its near-static score is overtaken by steeper upstream contractions, while processing and freezing retains rank 1. This uneven, rank-reordering shift is consistent with AE2, which anticipated a changed 2022 hotspot profile rather than proportional movement across all stages.

Table 9. Hotspot delta and rank shift, 2013–2022

stage_id	Stage	Sector proxy	SHS_2013	SHS_2022	Delta_SHS	Rank_2013	Rank_2022	Rank_shift	Direction
S5	Processing and freezing	Industry	85.27	56	-29.27	1	1	0	Decrease
S6	Export logistics	Services	53.57	46.88	-6.69	6	2	4	Decrease
S1	Hatchery and nursery inputs	Agriculture	79.76	37.68	-42.08	2	3	-1	Decrease
S2	Feed and farm inputs	Agriculture	79.76	37.68	-42.08	2	3	-1	Decrease
S4	Harvest and primary handling	Agriculture	79.76	37.68	-42.08	2	3	-1	Decrease
S3	Grow-out farming	Agriculture	79.76	37.68	-42.08	2	3	-1	Decrease

Note: $Delta\_SHS = SHS(2022) - SHS(2013)$ ***(Eq.4)***. *Descriptive-comparative; not causal.*

Table 10 decomposes each stage's delta into exact additive indicator contributions **(Eq. 5)**. The dominant driver varies by stage: hazardous child work (I4, −21.67) dominates the agriculture-proxied stages, child labor (I3, −21.91) dominates processing and freezing, and informality (I1,

−8.29) dominates export logistics. Weekly hours move in the vulnerability-increasing direction at the industrial and services nodes (+5.98 and +3.06, respectively). For the upstream stages, the combined child-related contribution (I3 plus I4 = −33.02) far exceeds the adult labor-market contribution (I1 plus I2 = −9.06). This contribution profile is inconsistent with AE3 because child-related indicators, rather than informality and working time, drive the observed shift at five of the six stages.

Table 10. Indicator-driver decomposition of the 2013–2022 SHS change

stage_id	Stage	Sector proxy	I1 Informality	I2 Weekly hours	I3 Child labor	I4 Hazardous child work	Total Delta	Dominant driver
S1	Hatchery and nursery inputs	Agriculture	-0.97	-8.09	-11.35	-21.67	-42.08	I4 Hazardous child work
S2	Feed and farm inputs	Agriculture	-0.97	-8.09	-11.35	-21.67	-42.08	I4 Hazardous child work
S3	Grow-out farming	Agriculture	-0.97	-8.09	-11.35	-21.67	-42.08	I4 Hazardous child work
S4	Harvest and primary handling	Agriculture	-0.97	-8.09	-11.35	-21.67	-42.08	I4 Hazardous child work
S5	Processing and freezing	Industry	-0.17	5.98	-21.91	-13.16	-29.27	I3 Child labor
S6	Export logistics	Services	-8.29	3.06	-0.51	-0.96	-6.69	I1 Informality

Note: Exact additive decomposition ***(Eq.5)****: each indicator's contribution is one quarter of its pooled-normalized 2013–2022 change, and the four contributions sum exactly to Delta_SHS (the 'Total Delta' column). Contributions are reported in SHS points, not as percentage shares, so the additive identity is preserved and the decomposition stays well-defined when a stage's Delta_SHS is small or its indicator changes are of opposite sign. The 'Dominant driver' is the indicator with the largest absolute contribution.*

Table 11 reports the export-exposure-weighted prioritization **(Eq. 6, 8, 9)**. Exposure weighting reorders the 2013 priorities relative to the raw SHS ranking: export logistics (S6) gains three positions (raw rank 6 to exposure rank 3), harvest and primary handling (S4) holds rank 2, and the lower-linkage hatchery, feed, and grow-out stages lose salience (rank changes of −3, −3, and −2, respectively). Processing and freezing (S5) retains rank 1 in both years. In 2022 the raw and exposure-weighted top ranks largely coincide, because the unweighted ranking already places S5 and S6 first and second, though exposure weighting still demotes the lowest-linkage stages within the tied agricultural block. In both years, the exposure-weighted ranking elevates export-linked stages above lower-linkage upstream inputs, providing qualified support for AE4; the reordering is substantially stronger in 2013 than in 2022.

Table 11. Exposure-weighted hotspot prioritization

stage_id	Stage	Year	SHS	SHS rank	Stage linkage w	Stage exposure	EWSHS	EWSHS rank	Rank change
S5	Processing and freezing	2013	85.27	1	1	0.667	56.85	1	0
S4	Harvest and primary handling	2013	79.76	2	0.75	0.5	39.88	2	0
S6	Export logistics	2013	53.57	6	1	0.667	35.71	3	3
S3	Grow-out farming	2013	79.76	2	0.6	0.4	31.9	4	-2
S1	Hatchery and nursery inputs	2013	79.76	2	0.5	0.333	26.59	5	-3
S2	Feed and farm inputs	2013	79.76	2	0.5	0.333	26.59	5	-3
S5	Processing and freezing	2022	56	1	1	0.333	18.67	1	0
S6	Export logistics	2022	46.88	2	1	0.333	15.63	2	0
S4	Harvest and primary handling	2022	37.68	3	0.75	0.25	9.42	3	0
S3	Grow-out farming	2022	37.68	3	0.6	0.2	7.54	4	-1
S1	Hatchery and nursery inputs	2022	37.68	3	0.5	0.167	6.28	5	-2
S2	Feed and farm inputs	2022	37.68	3	0.5	0.167	6.28	5	-2

Note: $EWSHS = SHS \ x \ (w\_link \ x \ E\_commodity)$ ***(Eq.6,8,9)****; E from WITS HS 030613 mirror imports after removing the EU-aggregate reporter. The commodity exposure E is a min-max blend of export value, quantity, and importer-concentration HHI normalized across the TWO observation years; with only two data points it preserves the direction of the 2013–2022 exposure decline but not its cardinal magnitude, so E and EWSHS should be read as an ordinal salience signal rather than a metric quantity. Rank 1 = highest priority; 'Rank change' is SHS rank minus EWSHS rank.*

Table 12 reports the PRCI coding and governance-adjusted residual-risk classification **(Eq. 10–12)**. Policy-response capacity is lowest at the agriculture-proxied input stages (PRCI = 0 for S1–S2 in both years) and highest at processing and freezing (50 in 2013; 60 in 2022), so the governance-adjusted residual risk (GRR) is greatest at the low-capacity, high-vulnerability upstream stages (GRR = 0.798 for S1–S2 in 2013). Under the within-year median split of normalized SHS and GRR, the critical category comprises S1, S2, and S3 in 2013 and S1, S2, and S6 in 2022—three stages in each year. Because the Critical residual-risk category is no smaller in 2022 than in 2013, AE5 is supported; its composition nonetheless changes, with grow-out farming exiting the Critical category as its PRCI improves and export logistics entering it.

Table 12. PRCI coding and governance-adjusted residual-risk classification

stage_id	**Stage**	**Year**	**P1 Legal**	**P2 Enforce**	**P3 Hazard rec.**	**P4 Remediation**	**P5 Due-diligence**	**PRCI**	**SHS**	**GRR**	**Residual category**
S1	Hatchery and nursery inputs	2013	1	1	1	1	1	0	79.76	0.798	Critical
S2	Feed and farm inputs	2013	1	1	1	1	1	0	79.76	0.798	Critical
S3	Grow-out farming	2013	1	1	2	1	1	10	79.76	0.718	Critical
S4	Harvest and primary handling	2013	1	1	2	1	2	20	79.76	0.638	Managed
S5	Processing and freezing	2013	2	2	2	2	2	50	85.27	0.426	Managed
S6	Export logistics	2013	2	2	1	1	2	30	53.57	0.375	Lower-priority
S1	Hatchery and nursery inputs	2022	1	1	1	1	1	0	37.68	0.377	Critical
S2	Feed and farm inputs	2022	1	1	1	1	1	0	37.68	0.377	Critical

stage_id	Stage	Year	P1 Legal	P2 Enforce	P3 Hazard rec.	P4 Remediation	P5 Due-diligence	PRCI	SHS	GRR	Residual category
S6	Export logistics	2022	2	1	2	1	2	30	46.88	0.328	Critical
S3	Grow-out farming	2022	1	1	2	2	1	20	37.68	0.301	Managed
S4	Harvest and primary handling	2022	1	1	3	2	2	40	37.68	0.226	Managed
S5	Processing and freezing	2022	2	2	3	2	2	60	56	0.224	Managed

Note: P1–P5 coded 1–3 from the USDOL country profiles for the 2013 and 2022 reporting years (U.S. Department of Labor, 2014, 2023). $GRR = SHS\_norm \times (1 - PRCI\_norm)$ ***(Eq.11)****. Median split* ***(Eq.12)****.*

Table 13 reports ranking stability under the equal-weight, child-risk-dominant, adult-labor-dominant, and child-risk-excluded specifications, together with exploratory Ward-cluster profiles. Processing and freezing retains rank 1 under the equal-weight, adult-labor-dominant, and child-risk-excluded specifications in both years, while the agriculture-proxied stages retain their relative position. The principal sensitivity concerns export logistics: in 2022, it exchanges position with processing and freezing under child-risk-dominant weighting and falls to last when child-risk indicators are excluded. Its elevated 2022 salience should therefore be interpreted as partly dependent on child-related indicators.

Ward clustering produced two moderately separated stage-year profiles, with an average silhouette width of 0.588. Cluster 2 contains the higher-risk 2013 profiles S1–S5, whereas Cluster 1 contains all six 2022 observations and S6 in 2013. Because SHS, EWSHS, PRCI, and GRR are analytically connected, the solution is interpreted as an exploratory structural diagnostic rather than as independent validation of the residual-risk categories.

Table 13. Robustness, sensitivity, and exploratory Ward-cluster profiles

stage_id	Year	Baseline rank	Child-weighted rank	Adult-weighted rank	Child-excl. rank	Residual category	Ward cluster	Silhouette	Residual-category comparison
S1	2013	2	2	2	2	Critical	2	0.66	Aligned
S2	2013	2	2	2	2	Critical	2	0.66	Aligned

stage_id	Year	Baseline rank	Child-weighted rank	Adult-weighted rank	Child-excl. rank	Residual category	Ward cluster	Silhouette	Residual-category comparison
S3	2013	2	2	2	2	Critical	2	0.68	Aligned
S4	2013	2	2	2	2	Managed	2	0.62	Mixed
S5	2013	1	1	1	1	Managed	2	0.32	Mixed
S6	2013	6	6	6	6	Lower-priority	1	0.28	Aligned
S1	2022	3	3	3	2	Critical	1	0.65	Mixed
S2	2022	3	3	3	2	Critical	1	0.65	Mixed
S3	2022	3	3	3	2	Managed	1	0.71	Aligned
S4	2022	3	3	3	2	Managed	1	0.68	Aligned
S5	2022	1	2	1	1	Managed	1	0.48	Aligned
S6	2022	2	1	2	6	Critical	1	0.66	Mixed

Note: Ranks are reported under equal-weight, child-risk-dominant, adult-labor-dominant, and child-risk-excluded specifications. Ward-cluster membership and silhouette values are exploratory profile diagnostics.

Table A 1 presents the cluster-profile statistics. Cluster 2 (n = 5) carries the higher residual-risk intensity, with mean scaled SHS of 0.907 and mean scaled GRR of 0.787, compared with 0.130 and 0.159 for Cluster 1 (n = 7). However, Cluster 1 has a Critical/Managed tie and Cluster 2 is Critical-dominant, so the profiles should be interpreted as diagnostics of relative residual-risk intensity rather than as a clean categorical separation. The separation is driven mainly by SHS and GRR, while PRCI differences are smaller, indicating that screened vulnerability and residual risk define the cluster boundary more strongly than governance capacity alone.

Figure 3 displays the sectoral social-risk indicator profile as paired 2013 and 2022 bars for each of the four core indicators across agriculture, industry, and services. The figure shows that the decline in the two child-related indicators is broad-based across sectors, that informality contracts most in services, and that weekly hours move in opposite directions in agriculture and industry. It makes visually explicit that no single sector improves uniformly across all four indicators, which is the sector-level basis for the non-uniform stage-level shifts reported in **Table 8** and **Table 9**.

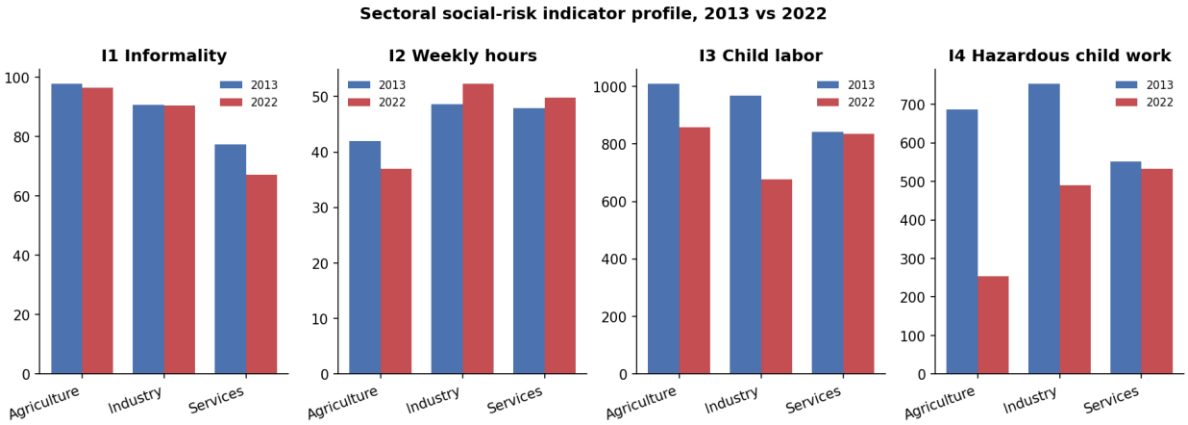

Figure 3. *Sectoral social-risk indicator profile*

Figure 4 presents the stage-level Social Hotspot Scores as paired 2013 and 2022 bars for the six chain stages. The figure shows processing and freezing as the tallest bar in both years, the four agriculture-proxied stages at an identical height, and a general compression of scores toward 2022. The visual gap between the processing node and the remaining stages narrows over the period, reflecting the steeper decline of the upstream segments against the more modest decline of the downstream processing node.

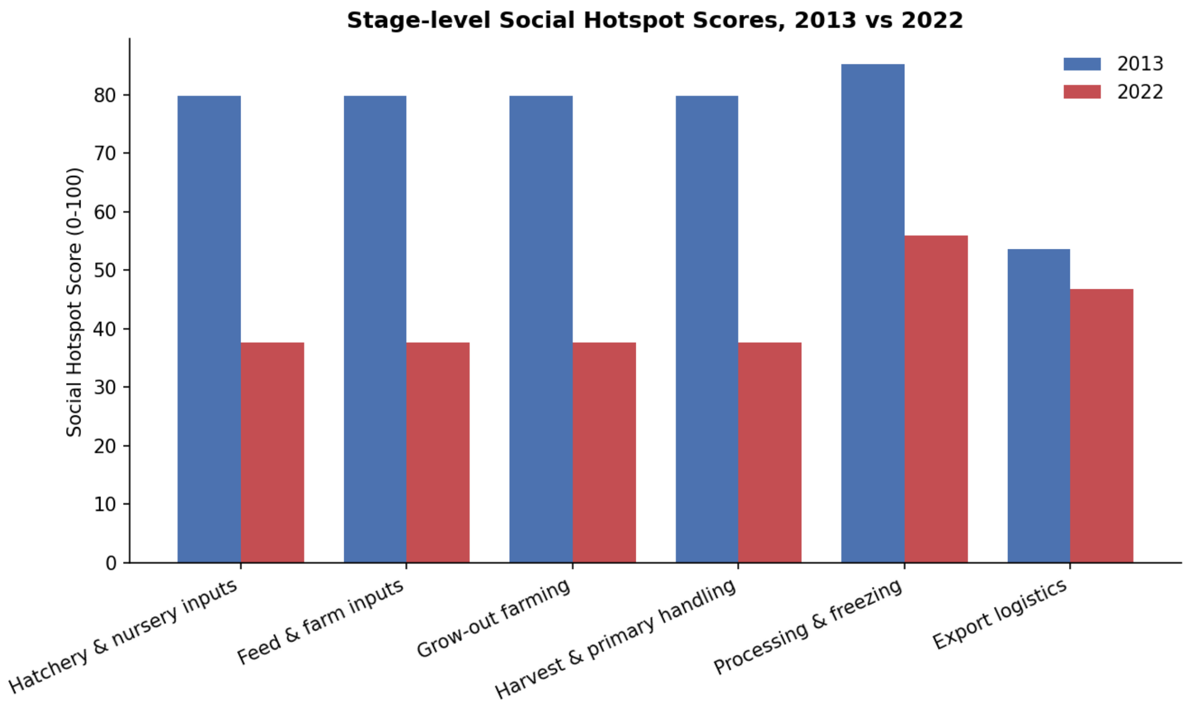

Figure 4. *Stage-level Social Hotspot Scores*

Figure 5 plots the SHS shift by stage as a slope chart connecting each stage's 2013 and 2022 score. Because the four agriculture-proxied stages are coincident, they are drawn as a single collapsed trajectory labeled accordingly, with processing and freezing and export logistics shown as separate lines. The steep downward slope of the agriculture-proxied trajectory and of the processing node, set against the shallow slope of export logistics, illustrates the rank crossover by which export logistics rises from last in 2013 to second in 2022.

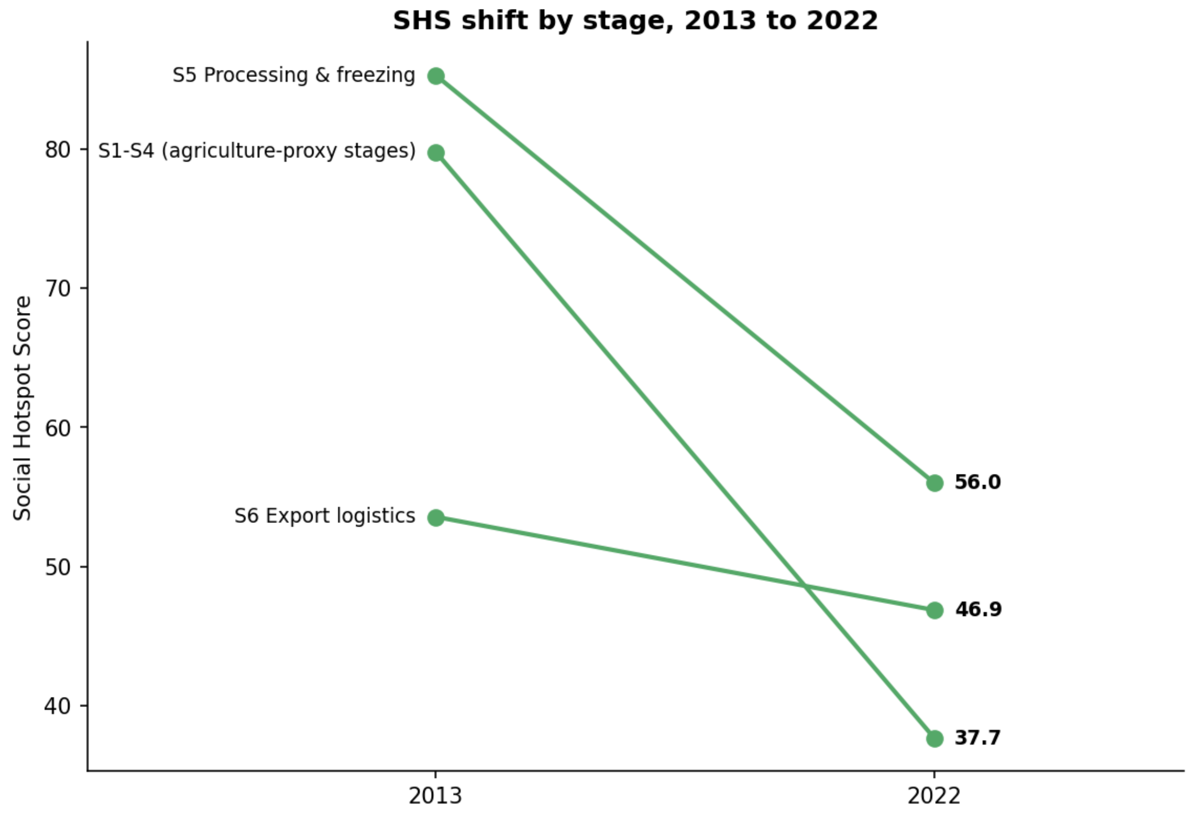

Figure 5. *SHS shift by stage*

Figure 6 visualizes the indicator-driver decomposition as signed stacked bars, with each stage's four indicator contributions summing to a total-delta marker. The figure shows the dominance of the hazardous-child-work segment for the agriculture-proxied stages and of the child-labor segment for processing and freezing, while the small positive weekly-hours segments at the industrial and services nodes sit above the zero line. The contrast between the large child-related segments and the small informality segments concentrates the visual weight away from the adult labor-market indicators.

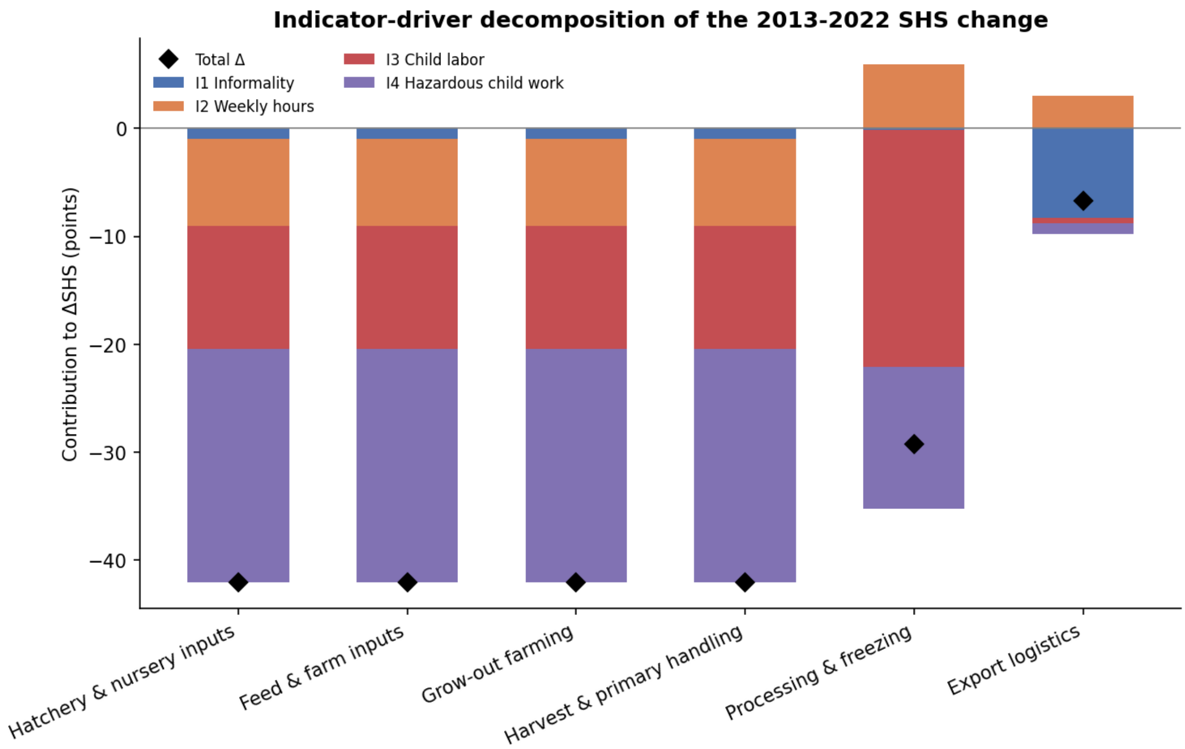

Figure 6. *Indicator-driver decomposition*

Figure 7 plots raw SHS against exposure-weighted SHS for each stage-year, distinguishing 2013 and 2022 markers. The figure shows the four agriculture-proxied stages, identical on the raw axis, separating along the exposure-weighted axis according to their stage-linkage weights, so that harvest and primary handling sits above grow-out farming, which sits above the coincident hatchery and feed stages. The downward and leftward migration of all markers between years reflects the joint decline in screened vulnerability and commodity export exposure.

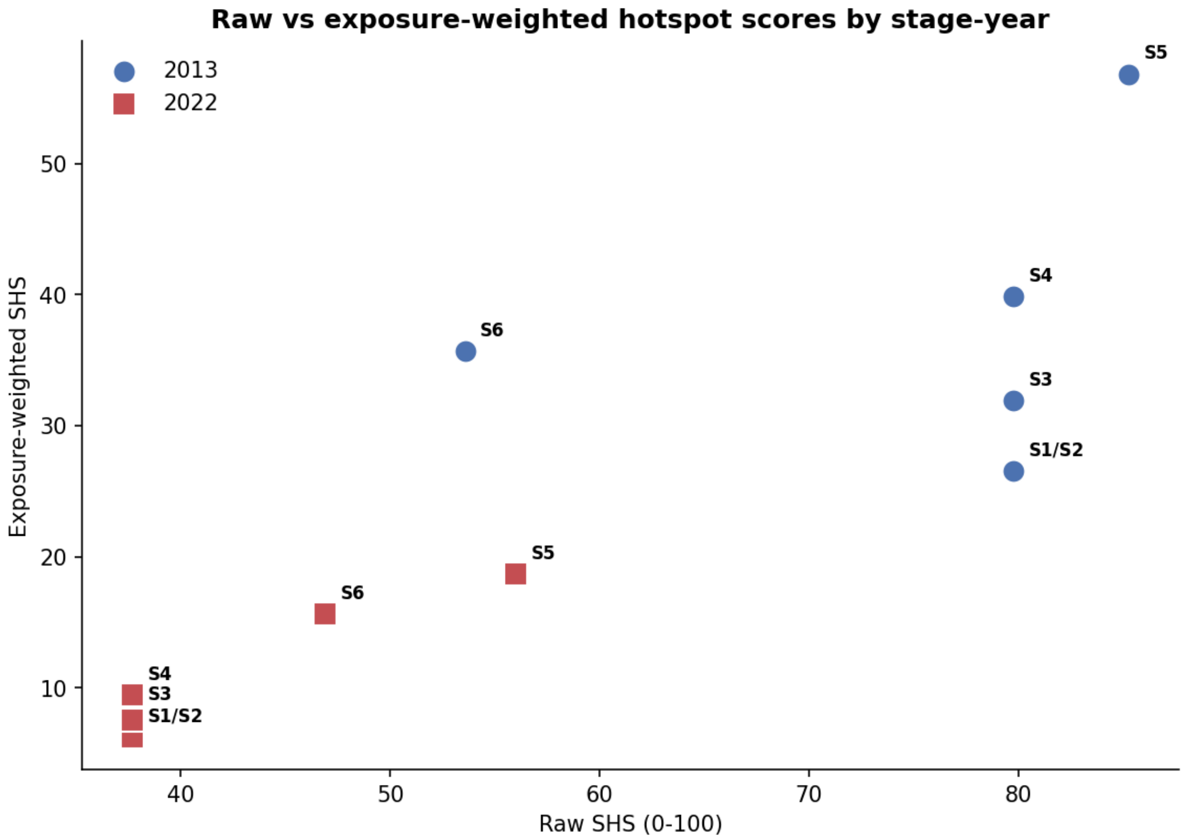

Figure 7. *Raw vs. exposure-weighted SHS*

Figure 8 supports AE5. Under the within-year median split of normalized SHS and GRR, the Critical category contains S1, S2, and S3 in 2013 and S1, S2, and S6 in 2022, so its size does not shrink. Its composition nevertheless changes: grow-out farming exits the Critical category, whereas export logistics enters because its modest SHS decline and limited policy-response capacity keep its GRR above the 2022 median. Processing and freezing remains the highest raw hotspot but is classified as Managed after governance adjustment, illustrating why residual risk rather than raw SHS should guide policy priority. The underlying PRCI coding and GRR values are reported in **Table** ***12***.

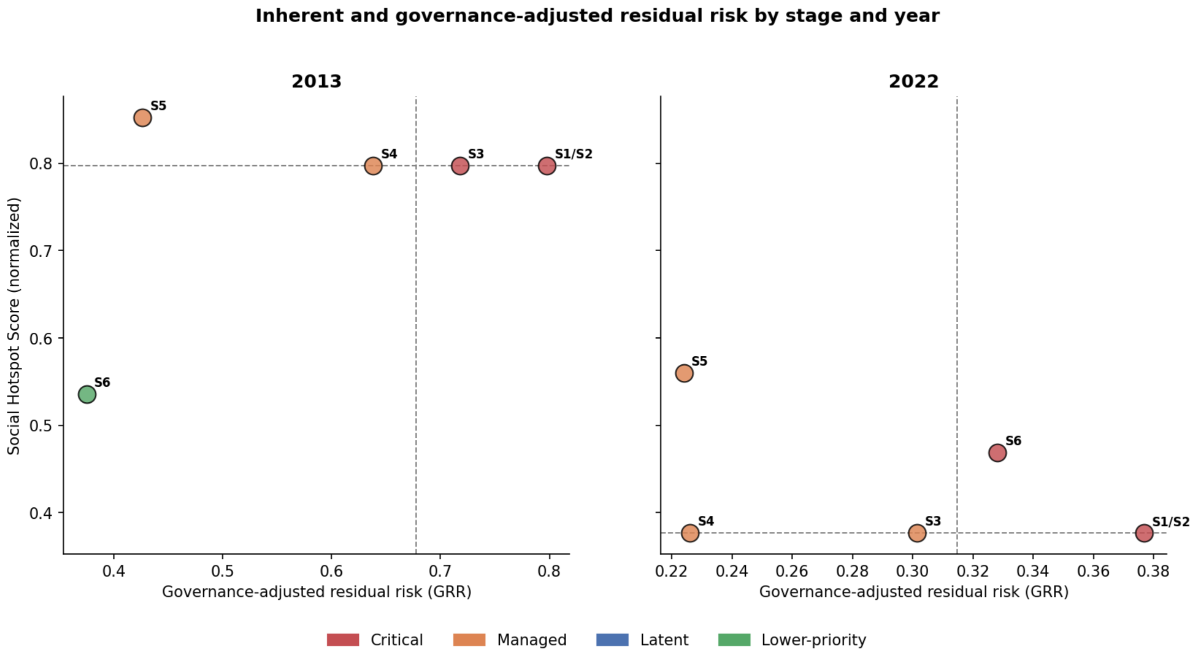

Figure 8. *Inherent and governance-adjusted residual risk by stage and year*

Note: *Categories are assigned from within-year medians of normalized SHS and GRR. PRCI enters the classification through* $GRR = SHS^{*} \times (1 - PRCI^{*})$*. The matrix is a descriptive screening device rather than a causal classification.*

Figure 9 displays the governance-adjusted residual risk as a stage-by-year heatmap, with color intensity proportional to GRR. The figure shows the highest residual risk concentrated at the agriculture-proxied stages in 2013 and a general lightening of the field toward 2022, consistent with the across-stage decline in screened vulnerability. The persistence of relatively darker cells at the low-capacity upstream stages indicates where residual risk remains comparatively high after governance adjustment.

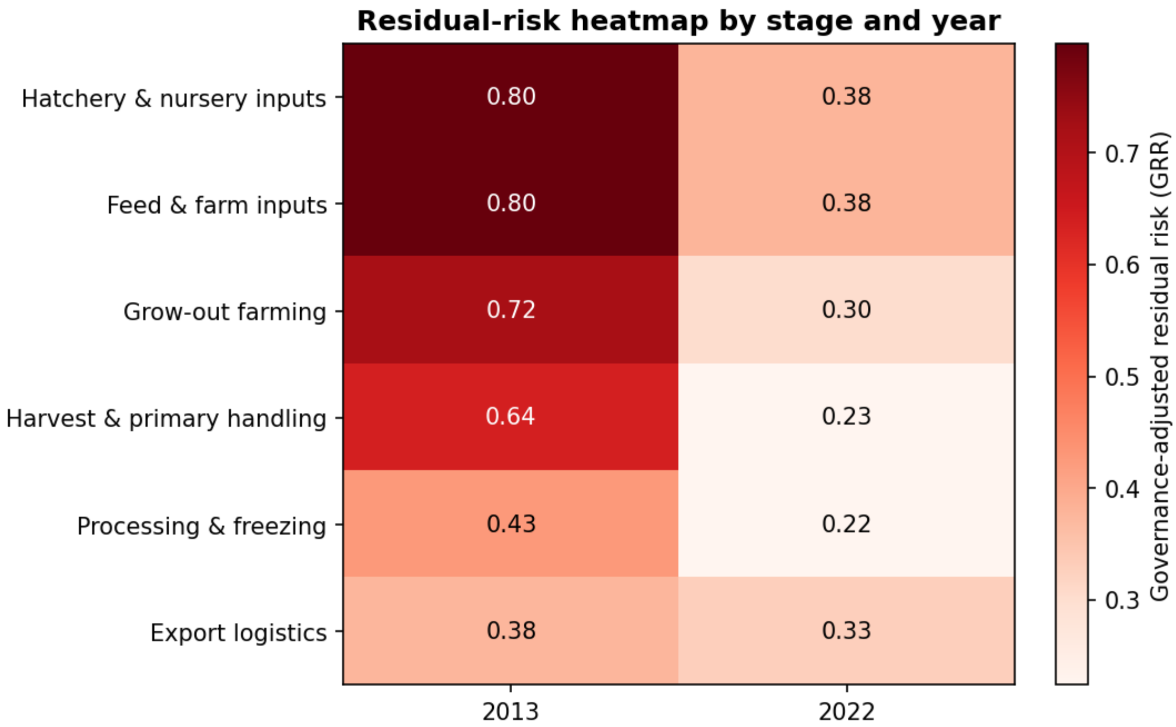

Figure 9. *Residual-risk heatmap*

Figure 10 presents rank stability across the robustness scenarios as paired heatmaps for 2013 and 2022, each cell giving a stage's rank under a given weighting or inclusion scenario. The figure shows near-constant rank coloring across the baseline, child-weighted, adult-weighted, and child-excluded columns for most stages, with visible reordering confined to the top of the 2022 panel under the child-risk-dominant and child-excluded specifications. The stability of the upstream block's coloring corroborates the robustness of its relative position.

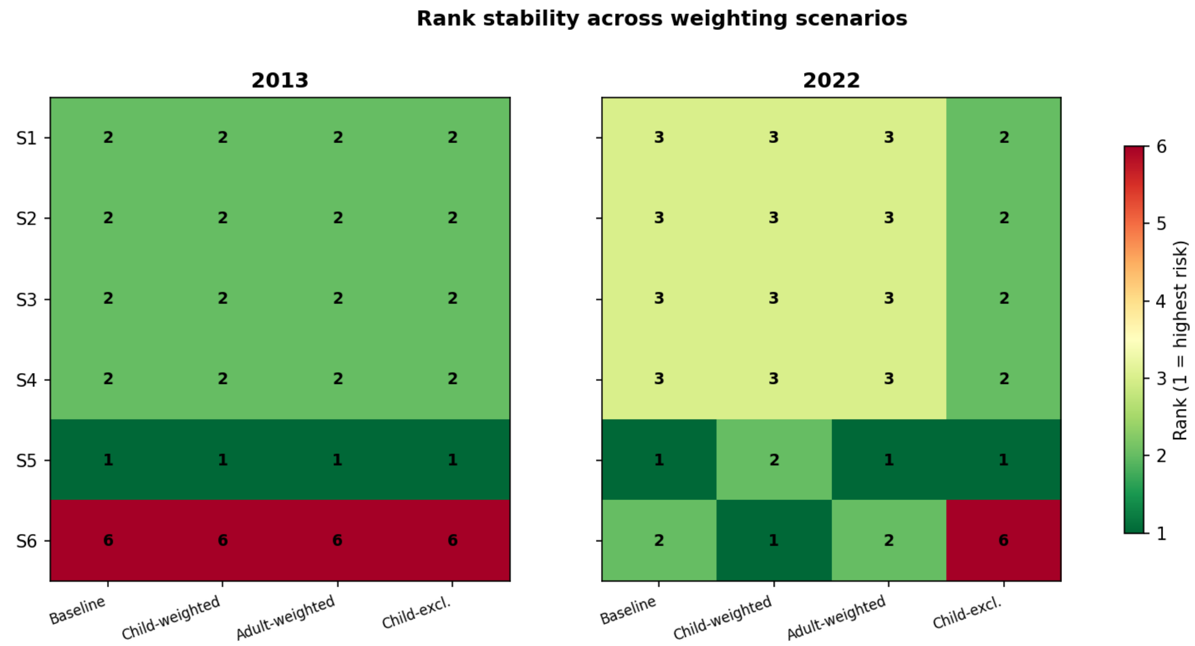

Figure 10. *Rank stability across scenarios*

Figure A 1 presents the Ward hierarchical-clustering dendrogram of the twelve stage-year observations. The principal partition largely separates the higher-risk 2013 profiles, comprising S1–S5, from a mixed lower-risk cluster containing all six 2022 observations and S6 in 2013. The agriculture-proxied 2013 stages merge at low linkage distance as the most internally similar group. The dominant split is therefore largely, but not perfectly, temporal.

Figure A 2 displays the clustered heatmap of the four scaled clustering inputs—SHS, EWSHS, PRCI, and GRR—with rows ordered by Ward-cluster membership. Cluster 2 is characterized by higher SHS, EWSHS, and GRR, whereas Cluster 1 contains lower and more mixed profiles. Because Cluster 1 has a Critical/Managed tie and PRCI differences are comparatively modest, the heatmap should be interpreted as a diagnostic of relative profile intensity rather than as categorical validation of the residual-risk matrix.

Chapter 6: Discussion

6.1 Main Findings Through Life Cycle Thinking

Through a Life Cycle Thinking lens, social risk in Bangladesh's frozen shrimp export chain is distributed unevenly across stages rather than concentrated at a single node. Processing and freezing records the highest raw screened vulnerability in both years (85.27 in 2013; 56.00 in 2022), the four agriculture-proxied stages share a single by-construction score—intermediate in 2013 but the lowest tier in 2022—and export logistics climbs from last to second (**Table 8** and **Table 9**). A factory-only assessment would have obscured the upstream-to-downstream gradient and the rising salience of the logistics interface. The raw ordering—formalized industrial node highest—runs counter to the displacement reading that locates risk at informal upstream and intermediate stages (Belton et al., 2017; Marschke et al., 2021).

Once governance capacity is incorporated, priority shifts away from the processing node toward weakly governed upstream and logistics interfaces: the most visible formal node scores highest, while policy-relevant residual risk concentrates where response capacity is weakest. The observed pattern is partly consistent with AE1: cross-stage heterogeneity is evident, but the formal processing node rather than an upstream informal interface records the highest raw hotspot. This stage-resolved map shows how screening sLCA identifies socioeconomic risk distributions within agri-food and agro-industrial systems rather than treating the export commodity as one undifferentiated sectoral unit (Tragnone et al., 2022; United Nations Environment Programme, 2020).

The identical baseline score across the four agriculture-proxied stages is a property of the proxy design rather than a claim of uniform conditions; the stages differentiate only at the exposure and governance layers, which is itself a life-cycle-consistent way to preserve upstream responsibility rather than treating the export node as socially isolated (Benoît Norris et al., 2014). The indicator decomposition reinforces the chain-distributed reading: the overall decline is carried by hazardous child work and child labor at the upstream and processing stages but by informality at logistics (**Table 10**), so the same downward movement has a different composition at different stages. This within-chain heterogeneity echoes evidence that labor regimes differ qualitatively across smallholder pond operations, industrial processing, and informal handling (Belton et al., 2017), and it supports calls to treat seafood social risk as chain-distributed rather than facility-bounded (Alexander & Kelling, 2024; Farmery et al., 2021).

6.2 Interpreting the 2013–2022 Shift

The hotspot profile improves overall between 2013 and 2022, but the improvement is uneven and, unexpectedly, concentrated in child-related indicators rather than adult labor-market structure. All six stages decline (**Table *9***); the agriculture-proxied stages decline most sharply, by 42.08 points, processing and freezing declines by 29.27 points, and export logistics declines least, by 6.69 points; this rank reordering is consistent with AE2. The decomposition is inconsistent with AE3: child labor and hazardous child work, not informality and working time, drive the change at five of the six stages (**Table 10**). This sectoral decline in child-related indicators should be interpreted against two competing global signals: the 2020 estimates documented the first global rise in child labor in two decades, while the 2024 estimates show renewed progress since 2020 but still report substantial hazardous work (International Labour Organization and United Nations Children's Fund, 2021, 2025). The divergence in this study most plausibly reflects long-run structural transformation and child-labor programming captured in modeled sectoral series, rather than verified worker-level conditions within shrimp-chain workplaces; cross-sectional proxies cannot isolate pandemic effects (Genoni et al., 2020; Marschke et al., 2021).

Several contextual pathways, none of them identified causally, plausibly shape the 2022 reading: supply-chain disruption and depressed farm-gate prices (Belton et al., 2021), labor-market stress and rural reverse migration (Genoni et al., 2020), school-attendance volatility (United Nations Children's Fund, 2021), and pandemic-era buyer cost-shifting onto suppliers and workers (Anner, 2022). The rising working-time contribution at the industrial and services nodes (+5.98 and +3.06; **Table 10**) is consistent with a price-and-sourcing squeeze in which fewer, more concentrated buyers press lead times and volumes onto a contracting supplier base (Anner, 2020); export value fell to USD 346 million while importer concentration rose to an HHI of 1,314 (**Table 7**). Because modeled ILOSTAT estimates may smooth pandemic-era reversals, the 2022 figures are best read as a post-pandemic comparison point rather than an estimate of pandemic-effect magnitude, consistent with the interpretive limits of generic-data screening (Díez-Hernández et al., 2026; Tragnone et al., 2022).

6.3 Agri-Food Versus Agro-Industrial Implications

Risk is not concentrated in one chain segment; the upstream agri-food stages and the downstream agro-industrial processing node carry different risk compositions, and the services-linked export interface is rising in salience. The upstream agri-food stages are child-risk-dominant and the weakest in governance capacity (PRCI = 0 for the input stages), so residual risk is highest there after adjustment (**Table 12**); agro-industrial processing carries the highest raw score but stronger governance capacity (PRCI rising from 50 to 60) and increasing working time even as child labor falls; services-linked logistics is informality-driven and enters the critical category in 2022. The implication for supply-chain upgrading is that interventions cannot be single-sector: upgrading the formal processing node through audits and certification leaves the upstream agri-food interfaces, where residual risk concentrates, largely untouched—precisely the displacement that Life Cycle Thinking is designed to prevent (Decker Sparks et al., 2022; Marschke & Vandergeest, 2016). This stage-resolved pattern supports the seafood-governance view that upstream and post-harvest informal segments concentrate under-monitored risk (Farmery et al., 2021; Finkbeiner et al., 2021).

The value-chain upgrading literature emphasizes that economic upgrading—higher-value processing and export—need not deliver social upgrading at upstream interfaces (Belton et al., 2017). The contracting and more concentrated export base raises the stakes: as documented for Bangladesh's export sectors, buyer-side price and sourcing pressure can transmit downward to the least-protected segments (Anner, 2020). A stage-differentiated map locates where social upgrading must be targeted—the agri-food input and handling interfaces and the rising services-linked logistics node—rather than at the already-monitored agro-industrial core.

6.4 Policy and Governance Implications

The governance-adjusted residual-risk matrix converts hotspot scores into a prioritized intervention map, and priority falls where screened vulnerability is high and governance capacity is weak. The critical category comprises hatchery, feed, and grow-out inputs in 2013 and the two input stages plus export logistics in 2022 (**Table 12**). That the Critical category is no smaller in 2022 is consistent with AE5 and indicates that legislative expansion alone has not shrunk residual risk: Bangladesh added hazardous sectors yet retained the same number of critical stages. For the upstream input and handling interfaces, the priority actions are extending inspection into small farms and informal handling that currently sit outside enforceable coverage, reactivating child-labor referral and remediation pathways, and formalizing pond-side handling, depot interfaces, and cold-chain logistics (OECD and Food and Agriculture Organization of the United Nations, 2016; U.S. Department of Labor, 2014, 2023). These priorities align with the policy-response literature that risk identification is insufficient without enforcement density and remediation capacity (Decker Sparks et al., 2022; Macchi & Bright, 2020).

The newly Critical services-linked logistics stage warrants extending due diligence beyond the processing gate. The OECD-FAO five-step cycle and government tools such as Comply Chain and the Better Trade Tool provide a risk-identification and remediation architecture, while this study adds the stage granularity needed to apply that architecture within the shrimp export chain (OECD and Food and Agriculture Organization of the United Nations, 2016; U.S. Department of Labor, 2023). The amended EU Corporate Sustainability Due Diligence Directive strengthens the relevance of such stage-level evidence because covered companies will be required, once the Directive applies from 26 July 2029, to address adverse human-rights and environmental impacts in their operations, subsidiaries, and chains of activities (European Parliament and Council of the European Union, 2024a, 2026), formalizing the due-diligence regime anticipated by Smit et al. (2020).

Because the raw hotspot rank—processing highest—diverges from the residual-risk priority—upstream highest—policy that follows the raw screening signal would over-invest in the already-monitored processing node and under-serve the critical upstream interfaces; the governance-adjusted classification corrects this misdirection. The robustness analysis shows the upstream block's position is stable across alternative weightings, whereas the elevated 2022 salience of logistics depends partly on the child-related indicators and should be monitored rather than treated as settled (Becker et al., 2017; Saisana & Saltelli, 2011).

6.5 Managerial and Supply-Chain Implications for Exporters and Buyers

For exporters, processors, and buyers, the stage map functions as a triage tool for allocating scarce monitoring resources. The exposure-weighted elevation of processing, harvest and primary handling, and export logistics (**Figure 7**) provides qualified support for AE4, showing why commercially salient stages should be considered alongside raw screened vulnerability when allocating due-diligence resources. The map separates four decision signals that a single audit rating conflates: raw labor vulnerability, export-exposure salience, governance-response capacity, and residual risk.

Its practical uses are to prioritize supplier engagement and remediation at the upstream agri-food interfaces and the services-linked logistics node rather than at the processing plant alone, to extend traceability upstream, and to treat rising importer concentration as both a risk—price and sourcing pressure transmitting to workers (Anner, 2020)—and an opportunity for concentrated, coordinated due diligence (European Parliament and Council of the European Union, 2024a). Facility audits at registered processing nodes systematically under-detect informal-interface risk (Decker Sparks et al., 2022), so the residual-risk map identifies where worker-voice and grievance mechanisms, not audits alone, are required (Finkbeiner et al., 2021).

structured due-diligence adoption shows a similar positive association (Samal & Jena, 2025).

Beyond triage, stage-level controls protect workers, supply-chain performance, and market access (Mani, Jabbour, & Mani, 2020; Samal & Jena, 2025). Supplier mapping, working-time records, remediation logs, and shipment-linked traceability can help prevent child labor, excessive working time, and hidden subcontracting abuses while showing EU buyers that identified risks are monitored and corrected. Weak documentation may prompt buyers to require corrective action, suspend orders, or change suppliers. From 14 December 2027, the EU Forced Labour Regulation prohibits products made wholly or partly with forced labor from being placed on or exported from the EU market; where forced labor is confirmed, competent authorities can prohibit, withdraw, and order disposal of the affected products (European Parliament and Council of the European Union, 2024b).

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Three firm-level allocation decisions follow from the divergence between raw and residual risk. First, assurance budgets should shift from repeat audits at registered processing facilities toward the upstream input and logistics interfaces: Villena and Gioia (2020) document that lower-tier suppliers are the least monitored and most hazardous links, and targeted audits detect concealed labor abuse more reliably than routine compliance cycles (Benstead, Hendry, & Stevenson, 2021). Second, upstream engagement should favor supplier development over termination, since Huq and Stevenson (2020) show that among Bangladeshi suppliers facing weak enforcement, buyer-supported capability building yields more durable compliance than policing, whereas exit displaces risk from view. Third, code requirements should be cascaded contractually to transport and cold-chain subcontractors, because lower-tier adoption occurs mainly where the buyer holds a meaningful share of the supplier's business (Wilhelm & Villena, 2021). The stage-resolved SHS–PRCI map supplies the quantified basis sLCA-oriented supply-chain management has sought for such decisions where firm-level disclosure is absent (D'Eusanio et al., 2019).

Stage-specific actions follow from the decomposition: at hatchery, feed, and grow-out inputs, supplier mapping and formalization incentives; at harvest, primary handling, and depot interfaces, child-labor monitoring and seasonal-labor protections; at processing, working-time controls given the rising hours contribution; and at logistics, informality and subcontracting checks. The contracting export base implies that engagement should be relationship-deep rather than audit-broad, since a smaller, concentrated buyer set can sustain longer-term supplier commitments (Anner, 2020, 2022). Responsible-sourcing claims anchored in processing audits alone risk overstating chain-wide assurance because the residual-risk map shows that upstream and logistics interfaces remain weakly covered.

For exporters and processors, the same evidence supports a market-access and supplier-positioning interpretation rather than a purely defensive compliance interpretation. Documented stage-level screening, corrective action, and upstream traceability may help processors compete for preferred-supplier status with concentrated European buyers; due-diligence readiness may shorten onboarding, differentiate bids on non-price criteria, and support order continuity as the amended CSDDD applies from 26 July 2029 (European Parliament and Council of the European Union, 2024a, 2026; Smit et al., 2020). With the top-five importer share at 75.0 percent in 2022, retaining any single major buyer is commercially decisive, which raises the option value of verifiable social performance relative to a dispersed buyer base. The buyer side holds the mirror-image opportunity: a concentrated market lowers the coordination cost of joint supplier-development programs, pooled upstream monitoring, and shared remediation funds organized along the OECD-FAO due-diligence cycle (OECD and Food and Agriculture Organization of the United Nations, 2016), so the concentration that transmits price pressure downward can equally be organized into collective due diligence—converting the squeeze channel documented by Anner (2020) into a coordination asset.

Implementation can run through existing management systems rather than new infrastructure. The SHS–PRCI map can be embedded in supplier scorecards and onboarding protocols—segmenting suppliers into standard, enhanced-monitoring, and corrective-action tiers, with onboarding evidence covering labor arrangements, age verification, subcontractor use, and grievance access—and refreshed as ILOSTAT and USDOL reporting cycles update; worker-voice and grievance channels merit financing as detection infrastructure at the informal interfaces where audit instruments structurally fail (Decker Sparks et al., 2022; Finkbeiner et al., 2021). The pandemic experience strengthens the resilience rationale: Trautrims, Schleper, Cakir, and Gold (2020) argue that joint demand and supply shocks heighten workers' vulnerability to severe labor exploitation precisely when buyers loosen onboarding screens, so firms that sustain stage-level monitoring through downturns protect supply continuity alongside workers. At the processing node, the rising working-time contribution identifies an immediate, factory-internal exposure—overtime limits are standard buyer-code items—whereas the upstream child-risk legacy calls for community-linked responses, such as school-retention support delivered jointly with buyers and public programs, that audit instruments cannot substitute for.

Two boundary conditions discipline this managerial reading. First, buyer leverage is double-edged: Anner (2020, 2022) shows that concentrated buyers can convert due-diligence demands into unfunded mandates that shift compliance costs onto suppliers and ultimately workers, so credible programs price social compliance into purchasing terms rather than layering requirements onto squeezed margins. Second, the instrument is screening-level: cost and capability gaps are the barriers managers report most frequently (Sajjad, Eweje, & Tappin, 2020), and suppliers under weak institutional enforcement may decouple formal compliance from actual practice (Huq & Stevenson, 2020), so commercial decisions with supplier-level consequences—delisting, order reallocation, public sourcing claims—require firm-level verification before proxy-based stage scores are acted on. Regional seafood precedents make the stakes concrete: documented labor abuses have triggered importer scrutiny, delistings, and emergency compliance responses, so exporters should treat unresolved stage-level social risk as a potential market-access threat rather than only a reputational concern (Marschke & Vandergeest, 2016).

6.6 Extended Bangladesh Governance Roadmap

Several implementation bottlenecks concentrate on exactly the stages the residual-risk matrix flags as critical. Legal-coverage carve-outs exclude small farms below ten workers, domestic work, and small-scale/informal supply-chain work; the inspectorate of roughly 400 officers covers a workforce exceeding 74 million; the maximum child-labor penalty stands near USD

47; export-processing-zone inspections require prior notice; and the labor-inspection-to-child-protection referral mechanism was not functional in 2022 (U.S. Department of Labor, 2023). Although hazardous-child-labor elimination and child-sensitive social-protection programs exist, their reach into informal supply-chain segments remains constrained, leaving the upstream and informal-interface stages—where remediation pathways are already thinnest—least served (U.S. Department of Labor, 2023; United Nations Children's Fund, 2021). Aligning factory-inspection authority, social-protection and remediation programs, and export oversight would help close the gap between legal recognition and stage-level enforcement (Hoque, 2024).

A defensible reform sequence follows the residual-risk ranking: first, extend inspection and hazardous-work recognition into pond-side handling, depots, and cold-chain logistics, where coverage gaps and residual risk coincide; second, formalize labor interfaces and raise penalties to deterrent levels; third, reactivate referral and child-sensitive social protection at scale; and fourth, align covered buyer-side due-diligence obligations under the amended CSDDD with domestic enforcement so that producing-country capacity and buyer-side leverage reinforce rather than substitute for each other (European Parliament and Council of the European Union, 2024a, 2026; OECD and Food and Agriculture Organization of the United Nations, 2016). Informal-sector coverage remains the binding constraint, because programmatic reach into unregistered ponds, depots, and cold-chain/logistics contractors is where remediation is weakest (Hoque, 2024; U.S. Department of Labor, 2023).

6.7 Limitations in Interpretation

Several limitations bound the interpretation. Sectoral proxies cannot verify firm-level or stage-level conditions, and the identical upstream baseline scores are an explicit design property rather than a measured uniformity (Sureau et al., 2018; Wu et al., 2014). Some variables, including working poverty and employment shares, are contextual rather than stage-specific, and the export-exposure score derives from a two-point normalization that is ordinal rather than cardinal. The 2013–2022 differences are descriptive comparisons, not causal pandemic estimates, and generic-data screening carries documented interpretive bias (Díez-Hernández et al., 2026; Tragnone et al., 2022). Because the raw hotspot rank diverges from the residual-risk priority, the screening signal must be read alongside the governance layer rather than in isolation. These constraints confine the findings to relative-risk prioritization, and validation through worker interviews, enterprise audits, and finer stage-level traceability is the necessary next step (Decker Sparks et al., 2022).

6.8 Extended Comparison with Broader Seafood and Global Labor-Risk Debates

The Bangladesh pattern—under-monitored upstream and informal-interface risk persisting beneath a more visible formal processing node—recurs across Asian seafood chains, where hazard exposure migrates toward weakly regulated intermediaries and pre-processing sites (Marschke & Vandergeest, 2016; Marschke et al., 2021). The buyer-side price and sourcing squeeze documented for Bangladesh's export sectors generalizes the commercial-pressure pathway to other commodities (Anner, 2020, 2022), while the blue-economy literature's neglect of labor and the documented limits of voluntary compliance tools situate the case within wider seafood-governance debates (Decker Sparks et al., 2022; Farmery et al., 2021). The stage-differentiated, governance-adjusted approach offers a transferable screening template for comparable export commodities where stage-level worker data are unavailable.

Chapter 7: Conclusion

7.1 Summary of Findings

Processing and freezing carried the highest raw Social Hotspot Score in both years; stage scores differed systematically, but the top hotspot was the formal industrial node rather than the anticipated upstream informal interface, making the observed pattern partly consistent with AE1. Screened vulnerability fell at all six stages in 2022, but the decline was uneven and rank-reordering: the agriculture-proxied stages fell most steeply while near-static export logistics rose from last to second, a pattern consistent with AE2.

Child-related indicators, not adult informality and working time, drove the change at five of six stages—hazardous child work in the agriculture-proxied stages, child labor in processing and freezing, and informality only in export logistics—an observed pattern inconsistent with AE3. Exposure weighting elevated the export-linked stages above the upstream inputs, providing qualified support for AE4, and the Critical residual-risk category contained three stages in each year—the two input stages throughout, with grow-out farming exiting and export logistics entering by 2022—consistent with AE5.

The headline ordering remained stable under sensitivity checks: processing and freezing held rank one under the equal-weight, adult-weighted, and child-excluded specifications in both years, the upstream block retained its relative position throughout, and Ward clustering produced two exploratory stage-year profiles, with seven classifications broadly aligned with the residual-risk categories and five showing mixed profiles. The only unstable point is the elevated 2022 salience of export logistics, which depends partly on the inclusion of child-related indicators.

7.2 Contributions

The study makes four contributions. Theoretically, it connects screening sLCA to the socially sustainable supply chain management (SSCM) literature. That literature specifies the firm-side instruments—assessment, collaboration, and supplier development—through which buyers act on identified risk, yet it lacks the chain-specific, stage-resolved evidence needed to target those instruments within a given chain (Villena & Gioia, 2020; Yawar & Seuring, 2017). A stage-differentiated screening sLCA supplies that evidence, positioning life-cycle assessment as the diagnostic layer the management literature presupposes but rarely obtains where firm-level disclosure is absent (D'Eusanio et al., 2019). Methodologically, the study develops a policy-augmented screening sLCA that joins hotspot scoring under the United Nations Environment Programme (2020) screening logic with a governance-response axis operationalized from the OECD and Food and Agriculture Organization of the United Nations (2016) due-diligence cycle. The result is a residual-risk classification rather than a raw vulnerability ranking, supplemented by exploratory Ward clustering that describes broad stage-year profiles within the multidimensional screening dataset.

Empirically, the study supplies the two-period, stage-level hotspot comparison of Bangladesh's frozen shrimp export chain that the reviewed literature does not contain, built from open labor, trade, and governance data on a cradle-to-export-gate boundary wider than the cradle-to-farm-gate scope that predominates in shrimp life-cycle studies—and therefore able to surface the post-harvest, processing, and logistics interfaces a farm-gate boundary omits (Pazmiño et al., 2024; Ruiz-Salmón et al., 2021). Practically, it converts screening sLCA into a sourcing-decision tool by separating four signals that a single facility-audit rating conflates—raw labor vulnerability, export-exposure salience, governance-response capacity, and residual risk—so that buyers and policymakers can act on where risk concentrates rather than on where monitoring is already densest. The originality lies in this integration: prior work offers stage-level sLCAs without policy augmentation, governance reviews without indicator integration, or single-year screens without temporal comparison, but none combines stage-resolved social hotspots, export exposure, and producing-country governance capacity into one residual-risk map linked to firm-level allocation decisions.

Because every input is open, equal-weighted, and rubric-documented, the framework transfers to other export commodities for which stage-level worker inventories are unavailable, extending the proxy-based screening tradition (Benoît Norris et al., 2014; Wu et al., 2014) with an explicit policy-response axis. The transparent construction also answers calls to integrate governance-side variables alongside indicator-side variables in agri-food assessments (D'Eusanio et al., 2019; Tragnone et al., 2022), demonstrating one auditable route—ordinal rubric coding of public governance narratives—through which that integration can be replicated.

7.3 Policy and Managerial Implications

The residual-risk classification, not the raw hotspot ranking, should steer intervention. Policy that followed the raw signal would concentrate resources on the processing node, which already operates under the chain's strongest inspection and audit coverage, and would leave the critical upstream interfaces—hatchery and nursery inputs and feed and farm inputs in both observation years—largely unattended. For these stages, where coded policy-response capacity sat at the rubric floor, three actions carry the highest priority: extending labor inspection and hazardous-work recognition into the small farms and informal handling sites where enforceable coverage and inspection reach are weakest; reactivating the referral pathways that connect inspection findings to child-labor remediation and child-sensitive social protection; and formalizing the pond-side handling, depot, and cold-chain interfaces through which seasonal and piece-rate labor enters the chain (OECD and Food and Agriculture Organization of the United Nations, 2016; U.S. Department of Labor, 2014, 2023). Increasing the deterrent effect of child-labor penalties belongs in the same package, because the persistence of the Critical residual-risk category indicates that legal codification alone has not reduced residual risk.

Downstream, the policy task is differentiated rather than uniform. Processing and freezing combines the chain's highest raw score with its strongest governance capacity, so the marginal action there is working-time monitoring, given that hours contributed positively to screened vulnerability at the industrial node even as child-related indicators fell. Export logistics, newly critical in 2022, warrants extending traceability, subcontracting checks, and informality monitoring beyond the processing gate to the buyer-facing movement of the commodity.

For buyers and exporters, the stage map indicates where due diligence under the OECD-FAO five-step cycle and tools such as Comply Chain and the Better Trade Tool should be applied (OECD and Food and Agriculture Organization of the United Nations, 2016), and the amended CSDDD strengthens the future evidentiary relevance of such stage-level identification because covered companies will be subject to the amended requirements from 26 July 2029 (European Parliament and Council of the European Union, 2024a, 2026). Rising importer concentration cuts both ways: it may transmit price and sourcing pressure toward the least-protected segments, and it concentrates leverage in fewer buyers who can coordinate due diligence if they choose to exercise it (Anner, 2020). Decker Sparks et al. (2022) show that facility audits under-detect informal-interface risk, so grievance mechanisms and worker-voice channels are required there. The reproducible score architecture offers firms a defensible screening input for stage-level ESG disclosure.

For exporters and buyers, the residual-risk map functions as a sourcing-management instrument rather than a compliance afterthought. Because facility audits systematically under-detect informal-interface risk (Decker Sparks et al., 2022) and lower-tier suppliers are the least monitored and most hazardous links (Villena & Gioia, 2020), assurance budgets are better shifted from repeat audits at the registered processing node toward the upstream input and logistics interfaces the map flags as critical. At those interfaces, Huq and Stevenson (2020) show that among Bangladeshi suppliers facing weak enforcement, buyer-supported capability building yields more durable compliance than policing or exit, so supplier development should be the default response, and code requirements should be cascaded contractually to transport and cold-chain subcontractors, where adoption depends on buyer leverage (Wilhelm & Villena, 2021). As importer concentration rises, documented screening and upstream traceability can become an order-qualifying capability and protect market access as the Union forced-labor prohibition becomes applicable in December 2027 (European Parliament and Council of the European Union, 2024b; Mani et al., 2020).

Sequenced nationally, the residual-risk ranking supports four steps: first, extend inspection and hazardous-work recognition into pond-side handling, depots, and cold-chain logistics, where coverage gaps and residual risk coincide; second, formalize informal labor interfaces and raise penalties to deterrent levels; third, reactivate referral mechanisms and scale child-sensitive social protection into informal supply-chain segments; and fourth, align buyer-side due-diligence obligations with domestic enforcement so that producing-country capacity and buyer leverage reinforce rather than substitute for each other (European Parliament and Council of the European Union, 2024a; OECD and Food and Agriculture Organization of the United Nations, 2016). Informal-sector coverage remains the binding constraint on every step.

7.4 Limitations and Future Research

The screening character of the evidence bounds what the conclusions can claim: sectoral proxies rank relative risk without verifying firm-level conditions, and the 2013–2022 contrast is a descriptive comparison rather than a causal pandemic estimate. The managerial reading is correspondingly bounded—proxy-based stage scores can direct where to look, but commercial decisions with supplier-level consequences, such as delisting or order reallocation, require firm-level verification before they are acted on. Future research should therefore validate the screened hotspots through worker interviews, enterprise audits, stakeholder engagement, and finer supply-chain traceability data, and should test whether stage-level screening actually reshapes firm-level outcomes—sourcing decisions, supplier social performance, buyer retention, and due-diligence capability—so that stage-differentiated hotspot assessment becomes a testable component of sustainable supply-chain strategy rather than only a diagnostic map. Integrating the social layer with environmental life cycle assessment and life cycle costing would then extend the framework toward a full life cycle sustainability assessment of the commodity (United Nations Environment Programme, 2020).

Two extensions are specific to the framework's machinery. Following Saisana and Saltelli (2011), expert elicitation could supply validated dimension weights for the PRCI in place of the equal-weight default, and longer multi-year panels from ILOSTAT or comparable national survey sources would convert the two-point comparison into a trajectory analysis that distinguishes gradual trend movement from year-specific fluctuation without causal attribution (Díez-Hernández et al., 2026). Mixed-methods research should also examine whether worker-voice mechanisms, grievance access, and remediation programs actually reach the informal interfaces identified by the residual-risk matrix, since formal compliance systems can appear complete while leaving the most exposed lower-tier labor segments outside practical protection.

Appendices

Table A 1. Full cluster-profile statistics by Ward cluster

Cluster	n (stage-years)	Mean scaled SHS	Mean scaled EWSHS	Mean scaled PRCI	Mean scaled GRR	Mean silhouette	Dominant residual category
1	7	0.13	0.157	0.257	0.159	0.587	Critical/Managed tie
2	5	0.907	0.595	0.16	0.787	0.589	Critical

Note: Ward clustering, k = 2, selected by maximum average silhouette width (0.588). Cluster statistics are descriptive profile summaries and do not independently validate the residual-risk categories.

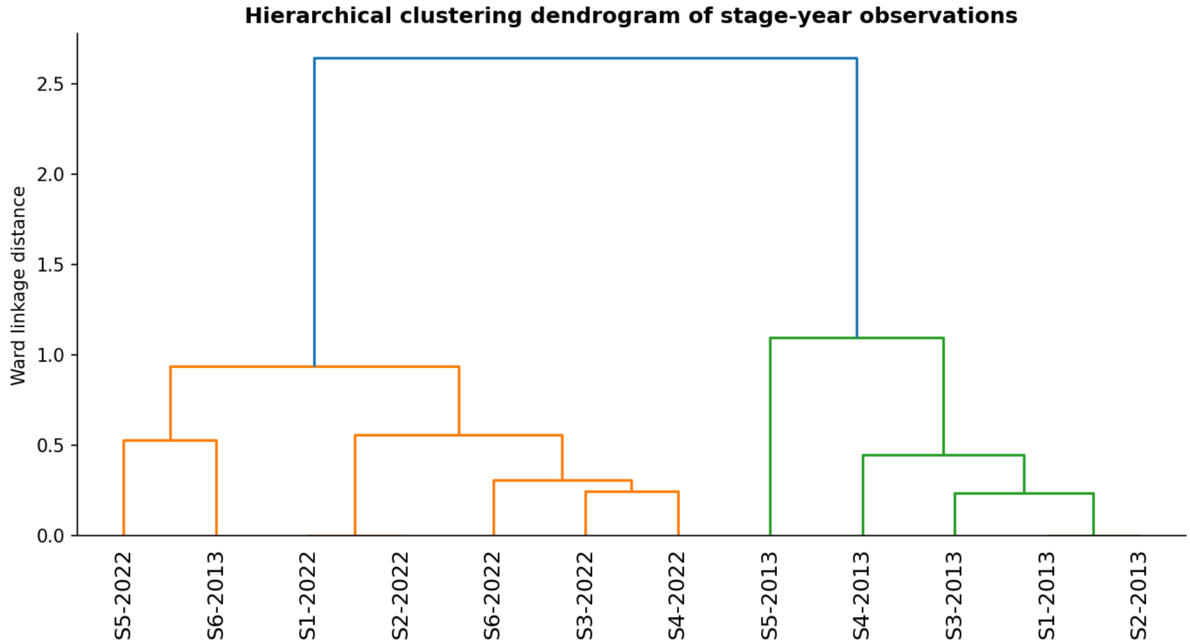

Figure A 1. *Hierarchical clustering dendrogram*

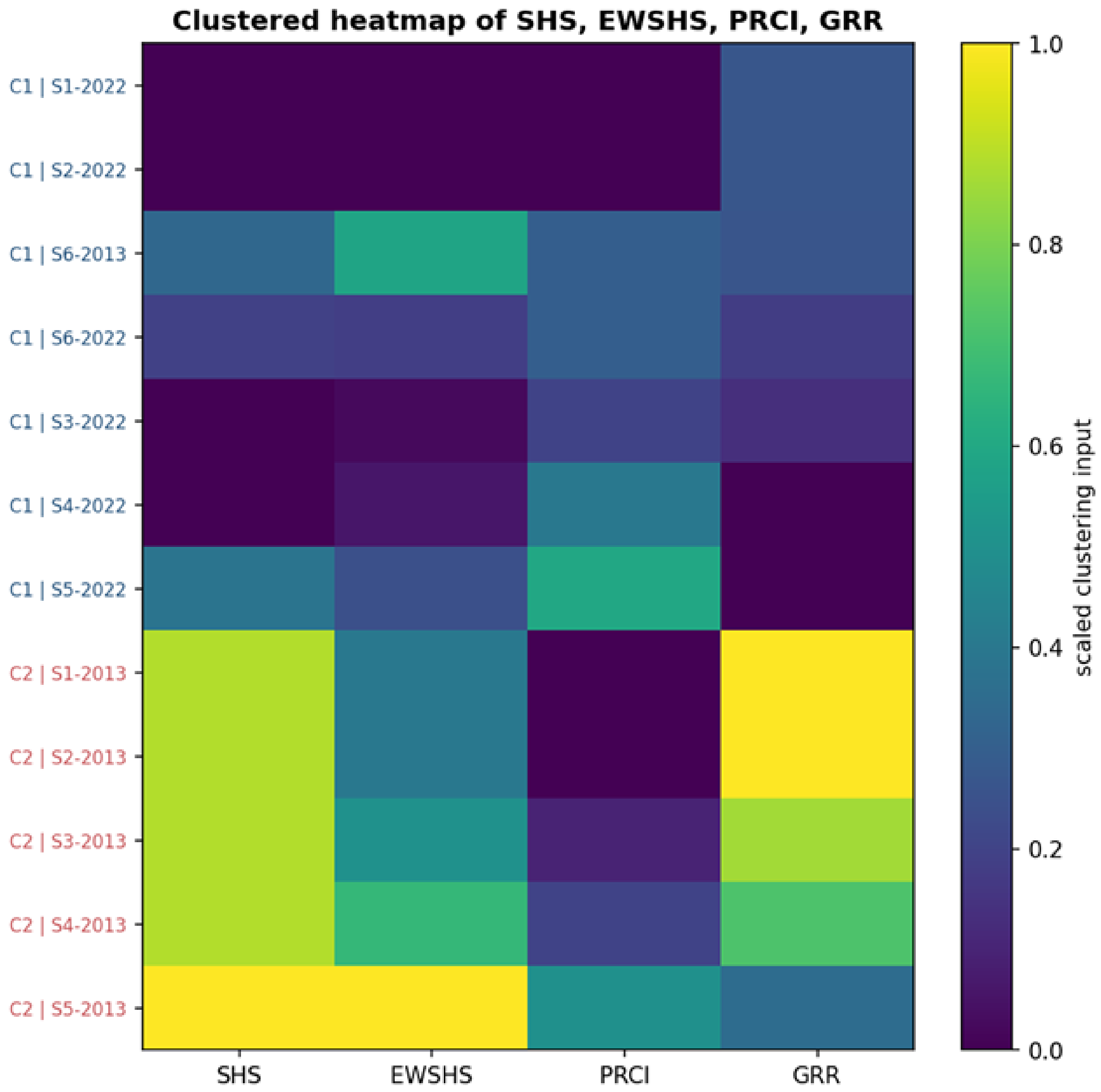

Figure A 2. *Clustered heatmap of SHS, EWSHS, PRCI, and GRR*

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