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Disruptive shocks in global agri-food value chains: a comparative analysis of impact trajectories across 12 case studies

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ABSTRACT

Agri-food value chains (AFVCs) are exposed to compound, complex climatic, geopolitical, and market shocks, yet prevailing resilience frameworks treat the impact of these disruptions as linear, sector-specific, and primarily from a technical perspective. This paper challenges such assumptions through a comparative analysis of twelve disruptive shocks and the associated impact trajectories affecting diverse AFVCs. Drawing on available mixed qualitative and quantitative evidence, the study applies and refines an accessible Resilience-Impact Assessment Framework (RIAF) to explore how distinct disruptive shocks propagate across interconnected nodes (production, inputs, logistics, trade, and governance), generating cascading and often non-linear impact(s).

The findings indicate that shock impacts and their trajectories are shaped less by the characteristics of the shock itself than by AFVC structure, institutional coordination, and the capacity to access buffering resources and implement adaptive responses. Highly concentrated, input-intensive, or weakly governed systems faced amplified disruptions cascading across nodes, whereas resilience emerged where redundancy, social capital, and polycentric governance absorbed shocks and enabled adaptive reorganisation. However, resilience was uneven across actors, places, and time. Indeed, AFVC operational continuity coincided with node-specific vulnerability for smallholders, marginalised producers, and other actors.

By foregrounding these interdependencies and impact trajectories, this research advances a more nuanced conceptualisation of resilience within AFVCs. Methodologically, it demonstrates the value of combining node-based analysis with qualitative insights to capture both material disruptions and relational dynamics. Building resilient AFVCs requires shifting from reactive crisis management to anticipatory, inclusive, and institutionally grounded governance that reduces system fragility and existing inequalities while enabling transformative, agile adaptation.

1. Introduction

Agri-food value chains (AFVCs) constitute the backbone of the global food system, coordinating the flows of materials, labour, energy, information, and finance that link producers, processors, traders, retailers, and consumers across space and time (Inoue and Todo, 2019). Over recent decades, these chains have delivered substantial gains in productivity, spatial integration, and market access (Helbing, 2013). However, this performance has been achieved through increasing production and sourcing specialisation, concentration, and compression of inventories, which have simultaneously intensified systemic fragility (Davis et al., 2020). As globalisation has deepened, interdependencies between spatially distant production and consumption regions have tightened, embedding AFVCs within complex webs of infrastructural, institutional, and ecological risk (Béné et al., 2023).

Disruptive shocks are a defining condition of contemporary AFVCs. Disruptive shocks are sudden, atypical events that generate multi-nodal disturbances across supply chain functions, triggered either by exogenous stressors (e.g., climatic extremes, geopolitical instability) or endogenous systemic failures (Craighead et al., 2007; Pettit et al., 2013) arising from internal breakdowns within AFVCs, such as infrastructure bottlenecks, market concentration, labour shortages, or governance failures. Climate change increases the frequency and intensity of extreme events (Intergovernmental Panel on Climate Change (IPCC), 2023), such as floods, droughts, heatwaves, and wildfires, while accelerating the emergence and spread of pests and zoonotic and

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phytosanitary diseases (Savary et al., 2019). Concurrently, geopolitical fragmentation, trade disputes, and armed conflict have destabilised historically reliable supply corridors, as seen in disruptions to Black Sea grain flows and fertiliser markets (Glauber et al., 2023). These disturbances, including acute shocks and longer-term structural stresses, rarely act in isolation; instead, they combine and interact with pre-existing socio-ecological vulnerabilities (within and between AFVCs), producing compound and cascading effects that propagate unevenly through AFVCs (Bren D'Amour et al., 2016).

This paper distinguishes between risks, shocks, stresses, and disturbances to clarify the scope of the analysis. Risks refer to potential future threats or vulnerabilities that may generate disruption if triggered (Manning et al., 2020). Shocks are acute, relatively rapid-onset disruptive events, such as floods, export bans, disease outbreaks, or infrastructure failures, that interrupt AFVC functionality over short to medium timeframes (Pettit et al., 2013). Stresses are slower-onset and longer-duration pressures, including drought, chronic market volatility, resource depletion, or geopolitical instability, which progressively erode adaptive capacity over time (Eriksen et al., 2021). Disturbance is used here as an umbrella term encompassing both shocks and stresses and their cascading effects across interconnected systems (Folke et al., 2021). Importantly, many contemporary AFVC disruptions combine acute shocks with pre-existing structural stresses, generating compound and interacting forms of systemic risk (Zscheischler et al., 2018; Béné et al., 2023).

The evolving character of systemic disruptive shocks marks a departure from earlier risk conceptualisations that treated disruptions as discrete, localised, and temporally bounded events (Manning et al., 2020). Evidence (see Zscheischler et al., 2018; Giaquinto et al., 2025) increasingly shows that AFVCs are exposed to slow-onset stresses and abrupt shocks that overlap and reinforce one another (Assefa et al., 2017), including climatic extremes, energy and input price volatility, labour shortages, and infrastructural bottlenecks (Kamalahmadi and Parast, 2016). Following the value chain concept, the impacts of these shocks are mediated not only through biophysical and market mechanisms, but also through governance arrangements, market power asymmetries, institutional design, and behavioural responses (Béné et al., 2023). Export bans, stockpiling strategies, biosecurity protocols, and consumer panic buying can amplify scarcity signals, distort price transmission, and accelerate disruption cascades (Munialo and Mellor, 2023). For example, during the early COVID-19 period, several major rice-exporting countries imposed temporary export restrictions while consumers simultaneously engaged in panic buying, which tightened global availability, drove rapid price volatility, and triggered precautionary stockpiling by import-dependent states, further intensifying market instability (Hobbs, 2020). This reinforces the tension between domestic production, consumption, and export markets, for critical staple commodities such as rice, whereby a comparatively modest disturbance to domestic production can have a pronounced impact on export capacity.

Responding to this analytical challenge, AFVCs have been framed as complex adaptive systems characterised by non-linearity, feedback loops, self-organisation, and emergent properties (Tendall et al., 2015). Within this perspective, resilience is understood not as a static attribute or isolated capacity (e.g., redundancy, flexibility, or robustness) (Kc et al., 2025), but as a relational and processual outcome shaped by interactions between diverse actors and institutions (Williams et al., 2023; Adger et al., 2018). However, many existing resilience frameworks rely heavily on bespoke simulation models, optimisation approaches, or highly data-intensive network analyses that can be difficult to operationalise beyond specialist research settings (Ivanov and Dolgui, 2021; Hosseini et al., 2019). While analytically valuable, these approaches are not always readily interpretable or usable for policymakers, practitioners, producer organisations, or local stakeholders operating under conditions of limited data and institutional capacity (Béné et al., 2023).

In response, the Resilience-Impact Assessment Framework (RIAF) is designed as a systems-focused, flexible, transparent, and comparatively accessible diagnostic and heuristic framework analysing disruptive shocks across AFVCs. Drawing on complex adaptive systems theory and relational resilience perspectives (Folke et al., 2021; Tendall et al., 2015; Williams et al., 2023), the framework conceptualises resilience as a relational and multi-dimensional property emerging through interactions between interconnected AFVC nodes, actors, and institutions. The RIAF disaggregates AFVCs into interconnected nodes, traces cross-node disruption pathways, and evaluates four resilience dimensions: absorptive capacity (maintaining function during disruption), adaptive capacity (adjusting practices and operations), anticipatory capacity (preparing for future disruption through planning and forecasting), and transformative capacity (structural or institutional reorganisation to reduce future vulnerability) (Béné et al., 2023; Folke et al., 2021). Combining node-level impact scoring, qualitative governance assessment, and comparative propagation analysis to evaluate how disruptive shocks and longer-term stresses shape differentiated resilience outcomes across actors and scales. The framework enables integration of mixed qualitative and quantitative evidence across diverse disruption contexts while remaining adaptable to stakeholder-informed assessment and decision-making . This is intended to provide a simple, transparent, and operational framework capable of supporting both retrospective evaluation and proactive impact mitigation through a more nuanced understanding of shock typologies and resilience pathways. Within the RIAF, resilience dimensions refer to the functional capacities through which actors respond to disruption, while resilience factors refer to the specific mechanisms, resources, or governance arrangements enabling those capacities in practice, such as redundancy, diversification, coordination, or flexibility (Meuwissen et al., 2019; Folke et al., 2021).

This paper operationalises the RIAF through a comparative analysis of twelve real-world disruptive shock events between 2019 and 2023 across multiple commodity systems and world regions (Rocha et al., 2022). The cases span rice, wheat, poultry, meat, vegetables, and horticultural export chains in South and Southeast Asia, Sub-Saharan Africa, Europe, North America, and Latin America. They include both slow-onset and acute climatic disturbances, e.g., Pakistan's floods and the Australian “Black Summer” bushfires (Akter and Grafton, 2025), animal and plant disease outbreaks (e.g., highly pathogenic avian influenza in the United States and the desert locust upsurge in East Africa), geopolitical disruptions (e.g., the blockage of the Black Sea grain corridor), and market and energy price shocks associated with the COVID-19 period (FAO, 2023a). Exploring this diversity of cases is methodologically deliberate: inclusion of different regional and commodity and impact variances permits systematic comparison of how distinct shock types propagate through different value-chain architectures (Otto et al., 2017) and governance regimes, and how resilience emerges, or fails to emerge, under contrasting structural conditions (Rocha et al., 2022; Duit et al., 2010). Three research questions guide this research:

RQ1. How do disruptive shocks manifest across diverse AFVCs in real-world contexts, and how do actors and institutions respond?

RQ2. What shock typologies, impact trajectories, and adaptive strategies can be identified? and.

RQ3. How effectively does RIAF capture these dynamics, allow for meaning cross comparisons, and what refinements are required?

Addressing these questions contributes to emerging debates on systemic risk and resilience characterisation in food systems by providing empirically grounded (Savary et al., 2020), cross-case evidence on the mechanisms through which disruption cascades unfold and are contained (Novoszel and Wakolbinger, 2022). By foregrounding context-specific resilience pathways, this study challenges universalistic prescriptions that dominate policy discourse (Grabs et al., 2021). Strategies such as supplier diversification, financial hedging, and technologically intensive biosecurity may be effective in high-income, capital-intensive systems (Fanzo et al., 2021), yet remain unfeasible or inequitable in smallholder-dominated and resource-constrained contexts (FAO, 2025). Conversely, informal, relational, and community-based coping mechanisms, frequently invisible in formal assessments, may be central to embedding stability in low-resource settings (Rocha et al., 2018). By coupling systems theory with comparative empirical analysis, this paper bridges conceptual debates and lived realities (Folke et al., 2021), offering empirically grounded insights on i) categorising and assessing the impacts due to supply chain disruptions and ii) how more effective, anticipatory, and socially just resilience strategies can be designed under accelerating global environmental change and systemic uncertainty.

The paper is structured as follows: Section 1 is the Introduction, and Section 2 provides a literature-informed reflection on the value of a comparative case approach in determining how disruptive shocks manifest in real-world contexts and how actors respond. Section 3 outlines the findings and the patterns that emerge from the evidence base. Section 4 provides a thematically driven discussion on how the research questions have been explored and evaluated. Section 5 concludes the paper.

2. Literature review: the value of a comparative case study approach

Within this study, resilience is conceptualised as the capacity of AFVC actors, nodes, and institutions to anticipate, absorb, adapt to, and potentially transform in response to disruptive shocks and longer-term stresses while maintaining critical system functions and reducing future vulnerability. Rather than treating resilience as a static or purely technical attribute, the RIAF conceptualises resilience relationally, recognising that resilience outcomes emerge through interactions between governance systems, infrastructures, market structures, and actor capacities across interconnected nodes. Importantly, the framework distinguishes between resilience dimensions and resilience factors. Resilience dimensions refer to broader functional capacities through which AFVCs respond to disruption, namely anticipatory, absorptive, adaptive, and transformative resilience. By contrast, resilience factors refer to the operational mechanisms, institutional arrangements, or resources enabling these capacities, including redundancy, diversification, flexibility, coordination, insurance systems, and governance coherence. This distinction is analytically important because similar resilience capacities may emerge through different institutional or infrastructural configurations across AFVC contexts. This framing draws on social-ecological systems scholarship (Folke et al., 2021; Tendall et al., 2015) while extending it through explicit attention to cross-node propagation dynamics, distributive outcomes, and differentiated actor vulnerability within AFVCs.

There is now a broad consensus that disruptive shocks in AFVCs are increasing in frequency, intensity (Intergovernmental Panel on Climate Change (IPCC), 2023), and interconnectedness under conditions of climate change, geopolitical fragmentation (Béné et al., 2023), and deepening market integration (Rocha et al., 2022). Yet much of the existing scholarship remains analytically fragmented. As mentioned in Section 1, a substantial body of work relies on stylised, model-based approaches that prioritise generalisability over contextual sensitivity (Hosseini et al., 2019), while parallel strands focus on single-shock or single-commodity case studies that offer depth but constrain the ability to identify cross-system commonalities (Götz et al., 2013). Both traditions have made important contributions, but they struggle to capture the dynamic, cross-scalar interactions through which disruptive shocks and longer-term stresses propagate, and the heterogeneity of resilience outcomes between actors, nodes, and places (Hosseini et al., 2019). Given the interrelationship between commodity (e.g., perishability) and value chain characteristics (e.g., storage availability) in informing resilience, this heterogeneity is arguably more relevant for AFVCs, and similar commodities may embody different risks depending on location and vice versa.

Model-driven analyses have been particularly influential in debates around global trade and price volatility, illustrating, for example, how export restrictions amplify international wheat price spikes (Schewe et al., 2017), or how fertiliser shortages transmit yield shocks across regions (Glauber et al., 2023). However, such models often assume frictionless logistics, homogeneous behavioural responses, and smooth institutional functioning, and their analysis may require bespoke or highly detailed datasets. These (often endogenous) assumptions obscure how infrastructural damage, gendered labour regimes, informal credit constraints, and differentiated land tenure systems (individually or collectively) influence adaptive capacity (the ability of actors or systems to adjust, cope, and respond effectively to shocks and stresses) in practice (Eriksen et al., 2021). Equally, such approaches do not necessarily meet the needs of non-specialist stakeholders who may need to assess value chain risks and resilience. Conversely, disaster-focused studies, such as detailed accounts of the 2010 Russian heatwave (Zemtsov et al., 2020), or the 2019–2020 desert locust upsurge in East Africa (Salih et al., 2020), have provided rich insights into local impact(s) and associated post-incident coping strategies, yet frequently remain weakly connected to broader systemic dynamics or perspectives on interlinked value chain effects (Gebregiorgis et al., 2025). This gap becomes particularly significant when considering shock dynamics across contexts (Fair et al., 2017): the literature often fails to explain why similar disruptive shocks generate radically different impacts across seemingly infrastructurally comparable AFVC systems.

Comparative case study approaches offer a distinctive analytical advantage in addressing these limitations because they enable systematic comparison of how resilience capacities, governance arrangements, and propagation dynamics vary across diverse AFVC structures and disruption types (Fair et al., 2017). Classic methodological scholarship emphasises their suitability for answering “how” and “why” questions in complex, real-world systems, precisely because they allow empirical observations to be embedded within their institutional, infrastructural, and socio-ecological contexts (Yin, 2018; Merriam and Tisdell, 2016). More recently, cross-case comparative research designs have been advocated within global environmental change research as a means of systematically comparing multiple social-ecological systems across different geographic or institutional contexts, enabling scholars to trace non-linear contributions and causality, and identify emergent system properties (Brinkley et al., 2025), and examine feedback loops in social-ecological dynamics (Folke et al., 2021). In the context of AFVCs, this is critical. The disruption pathway or impact trajectory of a flood affecting rice production in Pakistan differs fundamentally from that of a highly pathogenic avian influenza outbreak in the United States (US) poultry sector, not only because of the biophysical characteristics of the threats (Eakin et al., 2017), but because of differences in governance structures, infrastructural dependencies, actor power asymmetries, and climate exposure profiles that shape divergent resilience trajectories (Cottrell et al., 2019).

A further strength of comparative case study research lies in its capacity to integrate diverse and often marginalised forms of evidence (Sperotto et al., 2015). Quantitative datasets and formal reporting systems systematically under-represent informal practices, community-level coordination, and relational forms of risk management (Hosseini et al., 2019). (Indeed, the factors that may contribute to AFVC vulnerability, such as lack of organising or administration structures, may also contribute to under-representation and under-reporting of value chain disruption). Grey literature, local government reports, non-governmental organisation (NGO) situation updates, farmer testimonies, and union communications frequently reveal adaptive strategies that are invisible in conventional modelling exercises (FAO, 2023; Quigley et al., 2020). For example, informal seed-sharing arrangements following the 2022 floods in Sindh were central to restoring planting capacity (Ashraf et al., 2023), yet remained largely absent from the narrative on national recovery frameworks (Iqbal et al., 2024). Similarly, informal trader networks in West Africa routinely activate cross-border social and commercial ties to reroute commodities when ports close or borders tighten, illustrating relational forms of resilience that elude standard supply chain performance indicators (Touch et al., 2025).

Comparative analysis also enables longitudinal analysis of resilience dynamics, revealing how short-term coping strategies can generate longer-term resilience or, conversely, vulnerability (Maru et al., 2014). Supply chain scholarship has increasingly highlighted that actions perceived as "resilient" in the immediate aftermath of disruption may mask the gradual erosion of social, financial, and ecological buffer capacity (Folke et al., 2021). Household-level responses such as the liquidation of livestock, the depletion of savings, or the intensification of unpaid labour often stabilise the impact of disruptive shocks in the short term while deepening precarity in subsequent seasons (Eriksen et al., 2021). By examining multiple cases across shock types and regions, comparative approaches make it possible to systematically identify shared causes for resilience traps, rather than treating them as idiosyncratic, even unexpected outcomes. Despite these advantages, relatively few studies have consistently applied an analytical framework across multiple commodities and disruption types. While important work has examined the COVID-19 pandemic's impacts on food supply chains (Aday and Aday, 2020). Most analyses remain temporally and sectorally bounded (Li et al., 2021). This limits the ability to distinguish systemic patterns of vulnerability (recurring structural weaknesses across AFVCs) from context-specific anomalies and constrains the transferability of lessons on effective and inclusive policy pathways.

The challenge in, and value of, facilitating an accessible, iterative and transparent impact evaluation and comparison method underpins the objectives of the method proposed here. A further advantage of applying a structured comparative framework lies in improving analytical transparency and consistency across heterogeneous cases. Although resilience assessment inevitably involves interpretive judgement, structured scoring systems and comparative matrices provide a systematic basis for identifying recurring impact trajectories, resilience asymmetries, and adaptive patterns across cases. In this study, the RIAF scoring architecture functions not as a predictive model but as a transparent heuristic device supporting cross-case comparison, interpretive consistency, and evidence synthesis. The structured comparison of node-level scores was particularly valuable in distinguishing major structural disruptions from moderate adaptive adjustments across AFVCs.

Applying the RIAF and assessing the outcomes across multiple cases directly responds to this methodological gap. By enabling structured comparison of governance arrangements, infrastructural dependencies, and power relations, the comparative approach employed here advances debates on resilience as an emergent, relational, and politically contested process shaped by governance structures, institutional coordination, market concentration, and unequal access to adaptive resources (Kettele et al., 2025) rather than a purely technical property of supply systems (Tendall et al., 2015). In this sense, comparative case study research is not merely illustrative but constitutive of robust knowledge production for governing AFVCs under accelerating conditions of systemic risk (Manning et al., 2020). The application of case study analysis, underpinned by a consistent conceptual and evaluation framework, can therefore serve as both a heuristic and a practical tool for assessing, comparing, and improving AFVC risk management and resilience governance across diverse disruption contexts (Mcclunie-Trust et al., 2022).

3. Methodology

This study operationalises the RIAF through a structured comparative analysis of twelve disruptive shock events affecting AFVCs. The methodology adopts an interpretive and systems-oriented comparative logic aimed at identifying how disruptive shocks propagate, how actors respond, and how resilience capacities evolve across temporal and spatial scales. This aligns with complex systems (Lim-Camacho et al., 2017) and resilience scholarship (Rocha et al., 2022) which emphasise the strengths of iterative comparison, contextual sensitivity, and reflexive interpretation over linear inferential testing (Eisenhardt et al., 2016; Nicmanis, 2024). Importantly, the comparative application of the RIAF enables iterative refinement of interpretations across cases, allowing recurring propagation dynamics, resilience asymmetries, and governance patterns to be identified and reassessed across different commodities, geographies, and temporal contexts (Bene et al., 2023). This comparative structure also supports analysis of how resilience capacities evolve, distinguishing proactive anticipatory capacities that enhance preparedness and risk reduction before disruption occurs from absorptive capacities that maintain system functioning during disruption, as well as the longer-term adaptive and transformative processes across diverse AFVC settings. Specifically, a cross comparison of impact pathways can identify and pre-empt important common drivers of both impact and resilience. Equally, the accessibility of the structure allows for further heuristic activities such as participatory (back-casting) scenario generation, which can also enhance or assess anticipatory capacity.

Therefore, the RIAF should be understood as an analytical and comparative diagnostic framework rather than a predictive model. Accordingly, the purpose of this study is not to statistically validate the framework, but to evaluate its explanatory utility, interpretive consistency, and practical applicability across diverse real-world AFVC disruption contexts. Applying the framework comparatively across twelve heterogeneous cases enabled iterative refinement of scoring logic, propagation typologies, and resilience dimensions through repeated cross-case evaluation and triangulation of evidence sources.

3.1. *Case study selection*

Case selection followed a purposeful maximum-variation sampling strategy (Bryman, 2016), designed to capture diversity across three analytically significant dimensions: commodity type, geographical setting, and disruptive shock typology (Sperotto et al., 2015). First, to reflect the heterogeneity of global AFVC architectures, cases were selected from staple grains, high-value horticulture, and livestock systems (Biagini et al., 2014). Second, geographical variation ensured representation of regions characterised by contrasting governance arrangements, trade connectivity, and climate risk exposure, including South Asia, East Africa, Europe, North America, and Latin America (Eriksen et al., 2015). Third, the sample spans climatic shocks, animal disease outbreaks, geopolitical disruptions, and market-financial disturbances, reflecting the multi-threat landscape documented in contemporary food systems research (Distefano et al., 2018). Whilst not exhaustive, these reflect important disruptive archetypes which can inhibit the flow of multiple commodity types, including crude/bulk or more processed goods. This diversity of cases is methodologically deliberate because heterogeneous cases enable identification of recurring propagation dynamics, resilience asymmetries, and governance patterns across contrasting AFVC structures and disruption types. The recurrence of cross-cutting determinants of shock impact (or indeed resilience) is potentially consequential as this may point to cross-sectoral solutions.

Inclusion criteria for the cases required that the case had (i) a disruptive shock that generated cascading or cross-node impact(s); (ii) sufficient publicly accessible documentation to allow triangulated analysis; and (iii) identifiable actors and institutional arrangements that could be identified, and their role in the response processes (Gomez et al., 2021). Exclusion criteria removed cases where there were localised disruptions with no chain-wide propagation, insufficiently documented cases, and events understood only through modelling rather than real-world observation (Izquierdo et al., 2022). This strategy mitigates the limitations of single-case idiosyncrasy (Hamilton et al., 2020) and avoids the abstraction inherent in stylised system models (Negri et al., 2021). In this instance, both recurrence, divergence, and individual contextualisation are considered in terms of the promulgation of disruptive shocks, not merely their origin or direct impact.

3.2. Evidence synthesis and data collection

The RIAF methodology is designed for flexible application, incorporating differing data types and sources, and can be applied at different scales from sub to large-scale value chains.

To that end, data collection employed an iterative evidence synthesis approach consistent with recent advancements in mixed-methods resilience research (Quigley et al., 2020). Between March 2024 and July 2025, documents were identified through academic databases (Scopus, Web of Science), institutional repositories (FAO, WTO, UNDP, USDA), and curated media archives, producing a dataset comprising 77 peer-reviewed articles, 23 policy or industry reports, and 14 field-level or media accounts. Data was drawn from peer-reviewed literature, stakeholder consultations, official reports (FAO, World Bank, UNDP), satellite imagery, and infrastructure monitoring, then triangulated to ensure reliability and mitigate bias (Bidoglio et al., 2024). This aligns with FAO's Resilience Index Measurement and Analysis (RIMA-II) (FAO, 2016) and the OECD's Systemic Risk Typology (OECD, 2012), enabling methodological cross-case comparability. The breadth of sources reflects the hybrid nature of AFVC-related disruptions, where formal datasets often fail to capture informal exchange networks, relational coordination mechanisms, and community-led adaptive practices (FAO, 2023; Quigley et al., 2020). Triangulation of evidence sources followed Creswell and Creswell's (2018) multi-source verification logic, integrating quantitative indicators, such as production losses, trade volumes, price series, and logistics delays, with qualitative evidence such as farmer testimonies, government directives, industry statements, and NGO reports (Gallina et al., 2020). This mixed evidentiary foundation strengthens interpretive rigor and mitigates biases that emerge when AFVC analyses rely solely on formal economic or trade statistics, which often mask distributional and gendered vulnerabilities (Gephart et al., 2016).

3.3. Framework application

As the RIAF method is sequential, it is designed to facilitate standardised application (see the Findings section and supplementary material) across different settings. The RIAF was applied consistently across all cases as follows:

1. **Context and boundary definition:** Value-chain boundaries, system interdependencies, and governance structures were mapped using FAO chain profiles (FAO, 2025) and industry documentation (Higgins et al., 2010).
2. **Node identification:** Core nodes (input provisioning, production, processing, distribution, retail/consumption) were identified. Sub-value chains (e.g., milling, cold-chain logistics) were incorporated where relevant (Sturgeon, 2008).
3. **Shock characterisation:** Each shock was classified by origin, intensity, duration, geographic extent, and recurrence (Distefano et al., 2018).
4. **Node-specific impact assessment:** Impacts were scored on a -3 to $+3$ scale based on empirical indicators such as yield decline, perishability losses, transport disruptions, and contract or credit failures (Torresan et al., 2019). These indicators are intended to be flexible enough to be applicable to a range of settings, with a graduated range of impact. These scores are value chain stage dependent (see Tables 1, 1A, and 1B).
5. **Resilience scoring:** Resilience was evaluated using a structured 0–3 scoring system assessing four resilience dimensions: anticipatory capacity (preparedness and planning), absorptive capacity (maintaining function during disruption), adaptive capacity (operational adjustment and flexibility), and transformative capacity (structural or institutional change). Scores were assigned using evidence in the existing academic and grey literature relating to redundancy, coordination, flexibility, response capacity, contingency planning, and governance effectiveness (Kc et al., 2025). Lower scores indicated limited adaptive resources, weak coordination, or absence of contingency mechanisms, while higher scores reflected stronger institutional capacity, redundancy, flexibility, and preparedness (see Tables 1, 1A, and 1B).
6. **Response analysis:** Responses were coded as proactive, reactive, or delayed and categorised by actor type (state, private sector, community) (Haile et al., 2017).
7. **Outcome evaluation:** Short- and long-term recovery trajectories were assessed to determine whether resilience was strengthened, maintained, or eroded (DuPuis et al., 2022).

To reduce interpretive subjectivity, a two-stage recoding and expert-informed interpretation procedure was applied (Olmos-Vega et al., 2023). Initial scores were assigned using triangulated quantitative and qualitative evidence derived from peer-reviewed literature, institutional reports, infrastructure assessments, trade statistics, and documented stakeholder responses. As both a mitigation against subjectivity and a structured heuristic device to facilitate review and critical discussion, initial scores were independently re-reviewed two weeks later using the same evidence base (Bidoglio et al., 2024). Discrepancies (e.g., deviations in scoring for similar scale impacts) were resolved through transparent justification notes, and comparative consistency checks across cases. Additionally, scoring interpretation was informed by documented expert assessments contained within FAO, USDA, UNDP, WTO, and sectoral industry reporting, thereby grounding the scoring process in domain-specific expertise rather than solely author interpretation. This iterative recoding stage allows for the possibility for group application and triangulation of experience as both a diagnostic and heuristic device.

The scoring architecture was designed to support comparative interpretation and pattern identification rather than generate precise predictive metrics. Accordingly, scores function as structured comparative indicators enabling consistent cross-case analysis of relative vulnerability, propagation intensity, and resilience performance.

Anticipatory resilience within the RIAF was operationalised through evidence of preparedness-oriented actions undertaken before or during early stages of disruption, including forecasting systems, contingency planning, strategic stockpiling, diversified sourcing arrangements, insurance mechanisms, surveillance systems, and proactive governance coordination. This allowed the framework to distinguish reactive post-incident coping responses from pre-emptive resilience-building capacities.

3.4. Cross-case data analysis

Cross-case analysis followed variable-pattern and causal-process comparison methods outlined by Miles, Huberman, & Saldaña (2019). Comparative matrices were constructed to identify: common shock propagation pathways or impact trajectories (e.g., transport chokepoints, dependency on single input suppliers, institutional bottlenecks) (Bailey and Wellesley, 2017), patterns in impact curve shapes across nodes (e.g., immediate upstream collapse vs delayed downstream price transmission) (Brown and Kshirsagar, 2015); and divergences between “apparent resilience” (rapid visible recovery) and “substantive resilience” (capacity to avoid deeper vulnerability) (Ali et al., 2017). Less representative cases, such as those where informal trader networks stabilised supply despite institutional failure, were treated as diagnostic (see Tables 1, 1A, and 1B) rather than aberrant, offering insight into alternative resilience logics (Eisenhardt et al., 2016). This approach aligns with systems perspectives emphasising emergent behaviours, distributed adaptation, and the non-linearity of shock propagation (Marchand et al., 2016).

Table 1
RIAF application to Pakistan's rice value chain under the 2022 floods.

RIAF Component	Description			
1. Context mapping	Pakistan's rice sector contributes approximately 8% of agricultural GDP and sustains more than 2 million households, primarily in Sindh and Punjab, which together account for over 90% of national rice production (FAO, 2023). The 2022 floods coincided with the pre-harvest phase, simultaneously disrupting production, distribution networks, and market flows (Waseem and Rana, 2023).			
2. Node characterisation	Seven critical nodes were mapped (input suppliers, producers, collectors, processors, exporters/wholesalers, transporters, and retailers/consumers), forming a tightly coupled socio-technical network in which disruptions propagate rapidly across logistic, financial, and governance linkages (Notteboom et al., 2021).			
3. Shock profiling	Using RIAF's shock diagnostic criteria, the 2022 floods are classified as a **high-intensity, climate-origin, national-scale, low-frequency** disruptive event with compound propagation pathways (Béné et al., 2023). Between June and September 2022, unprecedented monsoon rains inundated one-third of Pakistan's land area, resulting in the loss of approximately 80% of Sindh's rice crop and 44% of national output (FAO, 2023; Qamer et al., 2023). Moreover, 13,000 km of roads were damaged, severing logistics to export terminals and amplifying supply chain stress (United Nations Development Programme (UNDP)-World Bank and Government of Pakistan, 2022).			
4. Node-specific impact assessment	Node-specific impact scores presented were derived from cross-validated secondary data (FAO, ADB, UNDP, World Bank, 2022–23) and expert interpretations following the multi-criteria decision analysis (MCDA) approach (Bidoglio et al., 2024). The production node emerged as the principal fragility point, demonstrating **impact asymmetry**, where initial physical disruption cascades through interdependent nodes (Izquierdo et al., 2022; Li et al., 2022).			
	Node	Impact Score	Qualitative Description (see Table 1A)	Justification
	Input Suppliers	–1	Moderate impact or Partial disruption	Floods occurred at harvest time; while production inputs (e.g., seed, fertiliser) themselves remained physically intact, the collapse in farmers' purchasing power and demand led to sharp order cancellations, reducing demand for input suppliers and triggering financial strain (FAO, 2023).
	Producers (Farmers)	–3	Severe System-threatening impact	Northern Sindh and Punjab saw over 80% of standing paddy destroyed, while national-level rice output dropped approximately 44%, resulting in widespread livelihood and asset loss, crop failure, and erosion of household income and food security (FAO, 2023; Iqbal et al., 2024)
	Collectors	–1	Moderate impact or Partial disruption	With farm-level production collapsing, inflows of paddy to local brokers declined drastically; additionally, many rural storage facilities were damaged or flooded, constraining their capacity to aggregate, store, or forward rice for processing (Qamer et al., 2023).
	Processors/ Millers	–1	Moderate impact or Partial disruption	Processing capacity was constrained by a shortage of raw paddy and damage to milling infrastructure (flooded mills, broken machinery), resulting in reduced output and prolonged downtime (Otto et al., 2017)
	Exporters/ Wholesalers	–1	Moderate impact or Partial disruption	Exports were delayed due to port congestion, logistical bottlenecks, and disrupted inland transport;. However, some continuity was maintained via alternate routing through Karachi; overall, throughput fell sharply (UNDP-World Bank & Government of Pakistan, 2022).
	Transporters (Road/ Rail Operators)	–2	High impact or Major disruption	Extensive damage to road and rail networks (flooded tracks, washed-out roads, bridge collapses) severely disrupted freight transport; rerouting was possible but inefficient and costly, causing substantial delays and supply-chain disruption (Li et al., 2022).
	Retailers/ Consumers	–1	Moderate impact or Partial disruption	Flood-affected districts experienced acute shortages of rice and associated commodities; local supply shortfalls, combined with increased transport costs and damaged distribution networks, led to price spikes and consumer-level scarcity (Shah et al., 2023).
5. Node-specific resilience assessment	Producers scored 0, reflecting the absence of insurance, financial buffers, or adaptive pathways, while exporters and input suppliers scored 2, enabled by institutional capacity and diversified sourcing. These patterns reinforce arguments that resilience is not uniformly distributed but socially and institutionally stratified (Béné, 2020).			
	Node	Resilience Score	Qualitative Description (see Table 1B)	Justification
	Input Suppliers	2	Moderate resilience or Partial adaptive capacity	Corporate contingency plans, diversified sourcing networks, and access to formal credit markets enabled moderate adaptability despite reduced rural demand, reflecting structurally embedded resilience capacities characteristic of well-capitalised upstream actors (Ali and Mahfouz, 2025; Béné, 2020).
	Producers (Farmers)	0	Very low resilience or Highly vulnerable	Extremely low resilience due to an absence of risk-transfer mechanisms (insurance), liquidity buffers (savings), or adaptive farming options (e.g., flood-tolerant seed, drainage), illustrating socially differentiated resilience deficits and exposure traps among smallholders (Waseem and Rana, 2023; Béné, 2020).
	Collectors	1	Low resilience or Limited adaptive capacity	Limited redundancy: small-scale intermediaries depend on volatile, farmer-linked supply chains and operate with minimal storage infrastructure, making them vulnerable to prolonged supply interruptions despite informal coping practices (Habibi et al., 2025; FAO, 2023a).
	Processors/ Millers	1	Low resilience or Limited adaptive capacity	Possess some redundancy through multiple milling sites and partial mechanisation; however, logistics breakdowns and power shortages curtailed their adaptive capacity, demonstrating vulnerability in capital-intensive nodes without systemic contingency planning (Iqbal et al., 2024).
	Exporters/ Wholesalers	2	Moderate resilience or Partial adaptive capacity	Demonstrated institutional flexibility by rerouting exports through alternative ports and renegotiating contracts, evidencing higher adaptive intelligence and relational capacity typical of globally connected firms (FAO, 2023; Folke et al., 2021).
	Transporters (Road/ Rail Operators)	1	Low resilience or Limited adaptive capacity	Highly fragmented coordination structures enabled improvised rerouting, but the absence of formalised contingency frameworks constrained systemic adaptation, producing only partial, short-lived resilience (United Nations Development Programme (UNDP)-World Bank and Government of Pakistan, 2022).

(*continued on next page*)

Table 1 (*continued*)

RIAF Component	Description			
	Retailers/ Consumers	1	Low resilience or Limited adaptive capacity	Short-term price adjustments, rationing, and small stock reserves helped mitigate immediate shortages; however, no formal contingency mechanisms or structural buffers were in place to prevent prolonged price shocks or supply volatility (Ashraf et al., 2023; Béné et al., 2023).
6. Response analysis	Government agencies and development partners deployed reactive relief measures, including cash transfers, subsidised inputs, and accelerated infrastructure repairs that mitigated short-term disruptions but did not strengthen systemic resilience capacities (Shah et al., 2023; United Nations Development Programme (UNDP)-World Bank and Government of Pakistan, 2022). Private actors, particularly millers and exporters, displayed higher adaptive behaviour by rerouting flows via Karachi and reallocating rice stocks, reflecting emergent but un-institutionalised learning mechanisms (Ivanov and Dolgui, 2021; Folke et al., 2021). Consequently, these responses functioned as **temporally bounded corrections** rather than drivers of transformative change.			
7. Outcome synthesis and evaluation	Post-flood recovery remained slow and uneven. National rice output remained nearly 40% below pre-flood levels one year later (Qamer et al., 2023), and more than 4.4 million people experienced temporary food insecurity (FAO, 2023). Economic losses in Sindh exceeded USD 540 million, while downstream inflation contributed to a 29% increase in staple food prices (United Nations Development Programme (UNDP)-World Bank and Government of Pakistan, 2022; Qamer et al., 2023). Persistent transport bottlenecks sustained supply-side fragility, confirming RIAF's capacity to capture both cascading disruptions and institutional inertia.			

Table 1A
Qualitative descriptions for impact scores.

Impact Score	Qualitative Description
−3	Severe/ System-threatening impact
−2	High impact/ Major disruption
−1	Moderate impact/ Partial disruption
0	Neutral or negligible impact
+1	Moderate positive effect/ Limited opportunity gain
+2	High positive effect/ Significant adaptive advantage
+3	Transformational positive effect/ Major strategic gain

Table 1B
Qualitative descriptions for resilience scores.

Resilience Score	Qualitative Description
0	Very low resilience/ Highly vulnerable
1	Low resilience/ Limited adaptive capacity
2	Moderate resilience/ Partial adaptive capacity
3	High resilience/ Strong adaptive and transformative capacity

Tables 2–4 should be interpreted sequentially rather than independently. Table 2 presents the detailed empirical evidence for each case study, focusing on actor responses, governance interventions, and resilience capacities. Table 3 synthesises the principal cross-case patterns of shock propagation, resilience outcomes, and equity implications emerging from these empirical observations. Building on this evidence, Table 4 abstracts recurring disruption pathways into broader conceptual shock typologies and governance priorities applicable across diverse AFVCs. This progression from empirical evidence to comparative synthesis and conceptual generalisation is intended to improve interpretability while preserving the transparency of the comparative analysis.

3.5. *Ethical considerations*

All documents used were publicly accessible, and the study did not involve human subjects or primary interviews. All analytical decisions and scoring rationales were documented to ensure transparency, replicability, and ethical integrity (Hosseini et al., 2019). Detailed scoring logic, indicator interpretation, and case-specific scoring rationales are provided in Supplementary Material 1 to enhance methodological transparency and reproducibility (see Tables 1, 1A, and 1B).

4. Findings

This section presents a comparative analysis of the 12 case-studies and explores how disruptive shocks manifested in real-world contexts, and their impacts, as well as how the impact trajectories differ across nodes, actors, commodities, geographies, and scales. To illustrate the RIAF application, one case study (the Pakistan's 2022 flood and its impact on country's rice value chain) is presented here in detail (see Table 1 and Fig. 1). This example demonstrates the node-specific resilience and impact scoring process used consistently across all twelve cases. The details of the findings for the remaining eleven case studies are provided in **Supplementary File 1**. In this paper, “responses” refer to immediate reactive actions undertaken during or directly after disruption, “recovery” refers to processes aimed at restoring system functionality and stabilising flows, while “resilience strategies” or “transformative interventions” refer to longer-term structural, institutional, or governance changes intended to reduce future vulnerability and enhance adaptive capacity.

By way of illustration, Tables 2 (Evidence from individual cases) and Table 3 (Empirical synthesis of cross-case findings) and the collective visualisation in Fig. 2 show that the disruptive shocks varied from rapid-onset climatic disasters (Pakistan's 2022 floods, Australia's bushfires) to systemic geopolitical and policy disruptions (Black Sea blockade, India and Indonesia's export bans) (see Supplementary File 1). Each triggered distinct propagation cascades, disrupting input flows, production processes, logistical nodes, and ultimately, consumer access. The RIAF's four-dimensional lens, capturing absorptive (maintaining function), adaptive (adjusting practices), anticipatory (preparing for future disruptions), and transformative (structural/systemic reconfiguration) capacities, helps to disentangle how diverse actors (governments, firms, cooperatives, and communities) mobilised immediate response tactics, recovery measures, and longer-term resilience strategies, and for whom these responses were effective (Folke et al., 2021). A salient insight is the differentiated vulnerability of sub-value chains. Input chains (seed, fertiliser, pesticide) emerged as both highly fragile and strategically central in multiple contexts. For instance, the Russia-Belarus fertiliser sanctions exposed the deep dependency of Brazil's maize sector on external nutrient supplies (see Supplementary File 1), pushing agribusinesses toward bio-fertiliser substitution and cooperative input procurement, illustrating a transition from short-term operational response tactics toward longer-term transformative adaptation strategies (FAO, 2023). Similarly, Pakistan's floods disrupted fertiliser and seed networks alongside rice production, showing how the collapse of input sub-chains can amplify production and export losses (FAO, 2025). In contrast, disruptive shocks hitting mid- and downstream logistics nodes (e.g., the Suez Canal blockage and the Black Sea ports crisis) demanded agility rather than redundancy, a pattern reflected in the resilience scoring (see Supplementary File 1), where actors in these nodes showed higher adaptive/agility indicators (e.g., rerouting capacity, supplier switching, real-time coordination) but lower redundancy scores (e.g., buffer stocks, spare capacity) (Fan et al., 2022). The rapid rerouting of shipping lanes via the Cape of Good Hope or EU “Solidarity Lanes” demonstrates how private logistics operators and supranational bodies co-produced recovery and adaptive resilience through coordinated rerouting strategies and operational flexibility, key markers of adaptive and anticipatory resilience (Ivanov and Dolgui, 2021). However, these cases also illustrate uneven resilience capacity: while exporters and shipping alliances reconfigured routes, small importing nations in

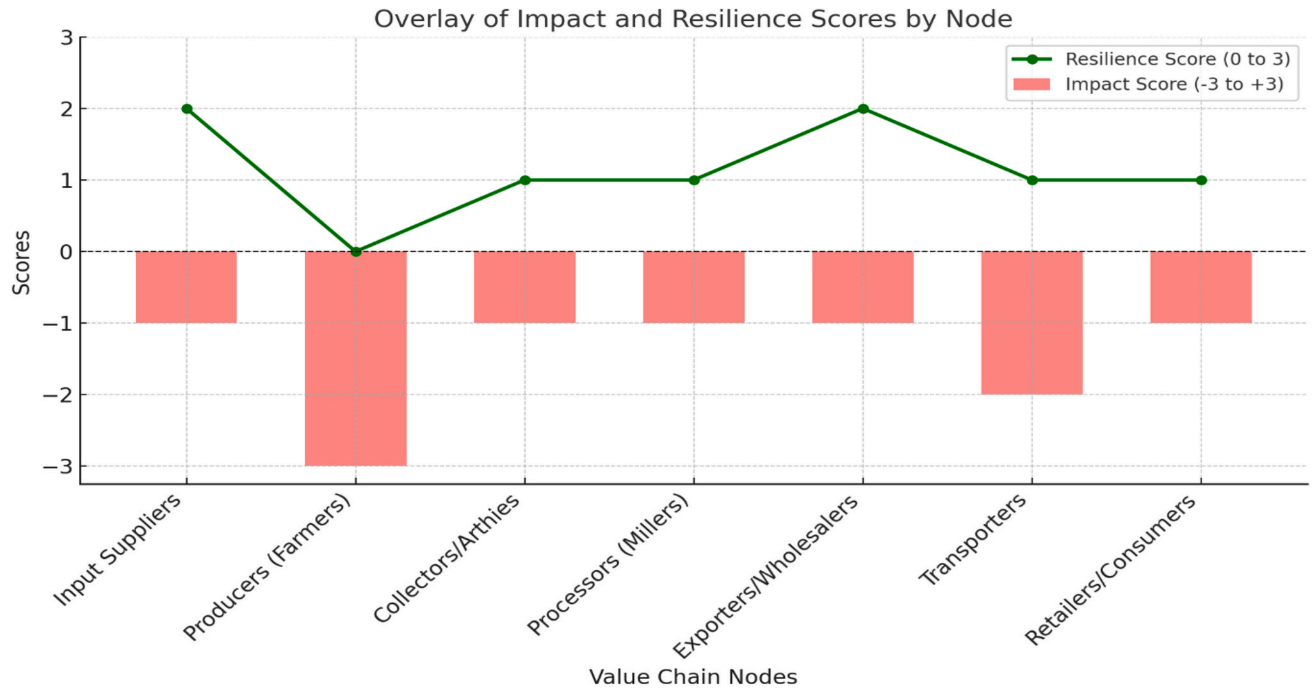

Fig. 1. Visual overlay of node-specific impact and resilience scores: Pakistan's Rice Value Chain under the 2022 Floods (Source: Author).

MENA faced rising food insecurity, signifying a distributive asymmetry in resilience outcomes (Béné et al., 2023).

The analysis foregrounds the distinction between operational response and recovery tactics and longer-term strategic resilience and transformation pathways (see Fig. 2, Tables 2–3). Strategic interventions (e.g., Italy's drought-resistant rice programmes or Morocco's greenhouse investments, see Supplementary File 1) strengthened long-term anticipatory, adaptive, and transformative capacities through technology adoption, governance reform, infrastructure investment, and institutional reconfiguration (Colon and Hochrainer-Stigler, 2022). Operational response and recovery measures (e.g., Argentina's cold-storage expansion, the USA's restocking schemes during the HPAI outbreak) reflect short-term agility and buffering, essential for immediate supply continuity but often reactive and resource-intensive (Meuwissen et al., 2019). Operational response and recovery tactics primarily supported short-term absorptive and adaptive capacities, whereas strategic interventions for longer-term resilience were more closely associated with anticipatory and transformative capacities. By distinguishing these tiers, the comparative case analysis extends beyond conventional food-system resilience metrics, such as recovery speed, production continuity, or output stability, that conflate short-term recovery and coping processes with longer-term structural transformation and resilience-building. The Pakistan and Kenya cases show both tiers co-evolving: emergency cash transfers and pest control (operational) worked alongside flood zoning and biopesticide innovation (strategic), representing the "nested temporality" of resilience cycles (Folke et al., 2021). Critically, the findings also assess the distributional effects of resilience strategies, identifying which actors benefit, which remain vulnerable, and whether response, recovery, and longer-term resilience strategies reinforce or reduce existing inequalities across AFVC nodes. In several cases, government-led or corporate strategies enhanced systemic robustness but marginalised smaller actors. For example, India's diplomatic export exemptions (see Supplementary File 1) stabilised regional markets but privileged state-level food security over smallholder incomes (Béné et al., 2023). Conversely, the Kenya locust outbreak response, where FAO supported community-based surveillance, illustrates participatory resilience that diffused adaptive capacity across social scales. This reinforces calls by Scoones and Stirling (2020) for more inclusive and justice-sensitive interpretations of resilience governance.

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Together, the twelve comparative cases give an explanatory context for the impact trajectories of disruptive shocks (from inputs to trade) and demonstrate how actor networks activate different resilience mechanisms across temporal and spatial scales. Across cases, RIAF score differentials indicate substantial upstream absorptive shifts in climatic and biological shocks (often >2-point increases), compared to more moderate downstream changes in logistical disruptions (typically 1-point shifts). Across cases, climatic and biological shocks generated the largest upstream score differentials (commonly >2-point shifts between impact and resilience stages), indicating major structural disruption and recovery asymmetries, whereas logistical and policy shocks more often produced moderate downstream shifts (typically ±1-point changes) (see Supplementary File 1), (Biagini et al., 2014). These quantified contrasts help distinguish major structural reconfigurations from incremental adjustments across nodes. The typology emerging from this analysis (Table 4 – Conceptual Synthesis) therefore situates resilience not as a singular outcome but as an evolving relational property, co-constructed through the alignment, or misalignment, of actors, institutions, and material infrastructures across global agri-food systems.

The research yields three overarching insights. First, disruptive shocks rarely operate as isolated events; instead, they propagate through interconnected socio-technical systems in non-linear and often asymmetric ways, as reflected in uneven score distributions across nodes and stages (see Fig. 2). Second, the severity and persistence of impacts are shaped less by the threat itself than by institutional configurations, governance coherence, and the distribution of adaptive capacity across actors and nodes, with larger score disparities signalling concentrated vulnerability within specific tiers. Third, prevailing response and recovery strategies frequently prioritise functional continuity over equity and ecological integrity, a pattern evidenced by higher continuity scores alongside limited improvements in equity-related indicators (Kc et al., 2025), so they are in danger of reproducing and deepening structural

Table 2
Observed resilience responses and governance strategies across the 12 case studies.

Case Study/ Year	Shock Type	Affected Commodity/ Sub-Chain and Key Impacts	Primary Actor Initiating Response	Observed Response Strategies	Response Scale	Dominant Resilience Capacity and Primary Beneficiaries	Key Data Sources/ References
Australia - Wine Grapes Bushfires (2019–20)	Climate (wildfire)	Wine grapes/ horticulture 1500 vineyards destroyed; "smoke taint" losses.	Industry Associations/ Growers	Firebreaks; insurance; smoke-taint mitigation, product blending; regional co-marketing.	Strategic (risk transfer); Operational (product innovation)	**Absorptive (farmers):** immediate livelihood buffering; limited **anticipatory** capacity. **Transformative (state):** Flood-zoning reform and climate risk insurance.	Akter and Grafton (2025);Wine Australia (2021); Folke et al. (2021)
Kenya -Sorghum Locust Outbreak (2020)	Biological (pest)	Sorghum & forage sub-chains >70% crop loss; feed scarcity; livestock distress.	FAO/ National Desert Locust Control Unit	Early-warning surveillance; biopesticide; fodder substitutions; community monitoring.	Strategic (monitoring system); Operational (pest control)	**Anticipatory Capacity (state, FAO):** predictive surveillance; **Adaptive Capacity (pastoralists):** feed diversification.	FAO (2023,2021); WFP (2020); Odhiambo et al. (2021)
Argentina -Beef Export Ban (2021)	Economic (policy)	Beef (export & feed chains) Export revenues ↓ US$1.3 billion; domestic glut.	Private Processors/ Exporters	Cold-storage; market diversification; poultry substitution; policy lobbying.	Operational (market substitution)	**Adaptive (processors):** market diversification. **Transformative (state):** trade reform.	FAO (2022). Bailey and Wellesley (2017).
India -Wheat Export Ban (2022)	Economic (trade restriction)	Wheat (grain trade sub-chain) Price surge +35%; SSA/MENA shortages.	National Government	Trade exemptions; commodity swaps; strategic reserves; price stabilisation.	Strategic (trade governance); Operational (commodity reallocation)	**Absorptive (consumers):** food price control; **Transformative (state):** strategic export management.	Reuters (2024); USDA (2024); Béné et al. (2023).
Indonesia -Palm Oil Export Ban (2022)	Economic (policy shock)	Palm oil (edible oil value chain) Global prices +45%; biodiesel/ feedstock disruption.	Government of Indonesia/ Private Refiners	Price caps; import diversification; supply chain digitalisation.	Strategic (trade governance reform); Operational (sourcing diversification)	**Adaptive (refiners):** supply substitution; **Transformative (policy):** digital traceability for export governance.	Reuters (2022); Shroff et al. (2024); Zaman et al. (2025)
Italy - Rice Drought (2022)	Climate (slow-onset)	Rice (irrigation sub-chain) Po River 70-year low; yield ↓ 30%.	Regional Water Consortia/ Farmers' Coops	Precision irrigation; drought-resistant cultivars; water-sharing.	Strategic (infrastructure & technology)	**Anticipatory (farmers, cooperatives):** long-term water governance; **Transformative (state):** reallocation of irrigation rights.	CBI (2024); ISPRA (2023); Meuwissen et al. (2019).
Pakistan – Rice Floods (2022)	Climate-induced (sudden-onset)	Rice (seed, fertiliser, logistics sub-chains) >80% crop loss in Sindh; 2.1 million hectares submerged; 4.4 million people food-insecure.	Provincial Govt/ FAO/ INGOs	Seed distribution; input vouchers; cash transfers; storage rehabilitation.	Mixed-Strategic (input rehabilitation) & Operational (cash transfers)	**Absorptive capacity (farmers, local traders):** buffer against immediate income and food loss, and limited anticipatory capacity due to weak preparedness mechanisms. **Transformative (state):** re-evaluation of flood zoning and climate-risk insurance pilots.	Mushtaq et al. (2022); United Nations Development Programme (UNDP)-World Bank and Government of Pakistan (2022); Qamer et al. (2023)
Russia-Belarus Fertiliser Sanctions (2022)	Geopolitical (trade)	Maize input sub-chains (fertiliser, logistics) Fertiliser ↑ 300%; yield ↓ 15%.	Private Importers/ Farm Unions	Stockpiling; bio-fertilisers; manure reuse; cooperative procurement.	Strategic (input resilience); Operational (stockpiling)	**Anticipatory (large farms):** stock management; **Transformative (agribusiness):** circular nutrient innovation.	Da Costa Nunes, 2025; FAO (2023b); FAO and WTO (2022); Colussi et al. (2024)
Suez Canal Coffee -Blockage (2022)	Geopolitical (logistics choke-point)	Coffee (shipping & port nodes) 12% global container flow delayed; EU coffee +15%.	Shipping Lines/ Trade Alliances	Alternate routes; emergency air freight; inventory buffering; logistics coordination.	Operational (logistics flexibility)	**Adaptive (importers, roasters):** temporal flexibility; **Transformative (shipping):** visibility tech adoption.	BBC (2021); Financial Times (2021); ICO (2021); ITC (2024).
Black Sea Ports Blockade (2022–23)	Geopolitical (war)	Wheat (export logistics, shipping) Ukrainian exports ↓ 40%; MENA food insecurity ↑; freight costs spiked.	EU Commission/ Ukrainian Rail Authority	Solidarity Lanes; grain corridor; logistics.	Strategic (infrastructure re-routing)	**Adaptive (exporters, traders):** rerouting and logistics flexibility; **Anticipatory (EU):** diversification of import origins.	USDA FAS (2024); Glauber et al. (2023); Ivanov and Dolgui (2021).
USA - HPAI Outbreak (2022–23)	Biological (zoonotic)	Eggs (input-production sub-chains) 43 million hens culled; retail prices tripled;	USDA APHIS/ Industry Alliances	Biosecurity; zoning; restocking incentives; risk insurance.	Operational (containment); Strategic (biosecurity upgrade)	**Absorptive (producers):** containment & cost-sharing; **Adaptive (retailers):** demand management.	USDA APHIS (2023); CDC (2023); Patyk et al., 2023)

(*continued on next page*)

Table 2 (*continued*)

Case Study/ Year	Shock Type	Affected Commodity/ Sub-Chain and Key Impacts	Primary Actor Initiating Response	Observed Response Strategies	Response Scale	Dominant Resilience Capacity and Primary Beneficiaries	Key Data Sources/ References
		processing disruptions.					
Spain Frost-Morocco Floods (2023)	Climate (extreme cold & rain)	Tomatoes (vegetable supply chain) Harvest losses ~50%; UK retail rationing.	Private exporters/ UK retailers	Greenhouse expansion; protected cropping; dual sourcing.	Strategic (facility investment); Operational (supply re-routing)	**Adaptive (retailers & exporters):** supply diversification; **Absorptive (growers):** protected cultivation.	DEFRA (2024); FAO (2023b); Guardian (2023); BBC (2023).

Notes: Table 2 presents the principal governance interventions, actor responses, and resilience capacities mobilised across the twelve AFVC disruptions. Resilience capacities follow the RIAF typology: absorptive (maintaining function), adaptive (adjusting practices), anticipatory (preparedness and contingency planning), and transformative (structural or systemic reorganisation). The table focuses specifically on response strategies and governance actions, while Table 3 examines propagation patterns, vulnerable nodes, and resilience outcomes separately. This separation improves analytical clarity between resilience responses and disruption pathways.
Table 2 focuses on actor responses, governance interventions, and dominant resilience capacities mobilised during each disruption event. Propagation dynamics and vulnerability trajectories are presented separately in Table 3 to improve analytical distinction between resilience responses and shock transmission patterns.

vulnerabilities rather than transforming them. Together, these findings advance a relational and justice-oriented understanding of food-system resilience (Brinkley et al., 2025), while exposing both the analytical value and current limitations of the RIAF framework. Furthermore, spanning climatic, biological, logistical, geopolitical, and policy shocks across five continents and multiple commodities (e.g., rice, wheat, maize, palm oil, beef, eggs, tomatoes, and wine grapes), the cases demonstrate that resilience is neither uniform nor neutral. Score variability across cases, ranging from marginal (±1) to pronounced (>3) shifts between stages, further underscores this unevenness (see Table 1 and Supplementary File 1). Instead, it is produced through uneven power relations, institutional choices, and network topologies that shape who absorbs risk, who gains access to recovery resources, who adapts successfully, and who benefits from longer-term resilience transitions (Zurek et al., 2022; Folke et al., 2021). The discussion section expands on these patterns, linking them directly to the questions posed in this paper:

5. Discussion

5.1. Shock manifestation and actor and institutional response (RQ1)

Disruptive shocks, by the innate nature of being disruptive, rarely remained confined to the node where they originated. Instead, perturbation is enacted through AFVCs via dynamic, multi-directional cascading impact trajectories that are shaped by AFVC structures, governance arrangements, institutional, and actor capacities. Disruption is non-linear, propagating through material, financial, and informational linkages, often intensifying as it encounters structural vulnerabilities (Chabot and Bertrand, 2025; Bebber et al., 2023; Folke et al., 2021). The direction, severity, and persistence of impact trajectories within the 12 cases (see Fig. 2 and Supplementary File 1) were mediated less by the threat itself (drought, blockage, floods, or export ban) than by the socio-technical configuration of the value chain, particularly concentration of resources, structural integration, and equitable access to buffering resources and the ability to deploy and benefit from adaptive capacity.

Climatic and environmental shocks illustrate this pattern clearly. For instance, Pakistan's 2022 floods, Kenya's 2020 locust invasion, and Australia's 2019–20 bushfires all originated at the production node, yet their most enduring consequences emerged downstream. In Pakistan, while over 80% of Sindh's rice crop was lost (FAO, 2023), prolonged disruption stemmed from damaged roads, storage, and power infrastructure that paralysed milling and transport for months, dislocating both domestic markets and exports (FAO, 2025). Whilst more resilient infrastructure cannot compensate completely for harvest losses, infrastructural vulnerabilities at any node in the AFVC serve to reduce the effectiveness of resilience and recovery efforts at the farm level, demonstrating the risks of considering resilience as a uni-nodal trait.

Similarly, the East African locust outbreak cascaded beyond crop losses into feed shortages, urban food inflation, and fiscal strain (FAO, 2023). In Australia, smoke taint, an invisible quality degradation, depressed wine exports long after vineyards resumed production (Wine Australia, 2021). In each case, interconnecting nodes acted as amplifiers, concentrating risk through logistical and infrastructural chokepoints. These observed dynamics align with Ivanov and Dolgui's (2021) concept of ripple-effect propagation, where shocks intensify as they move through tightly coupled systems. Spatial concentration and limited redundancy, narrow transport corridors, and centralised processing hubs translated localised node-centred damage into systemic disruption, echoing earlier findings from the Thai floods (Tanoue et al., 2020) and the Russian drought (Hunt et al., 2021). Such non-linear amplification is characteristic of complex adaptive systems, where losses at highly centralised nodes reverberate across the network (Lim-Camacho et al., 2017).

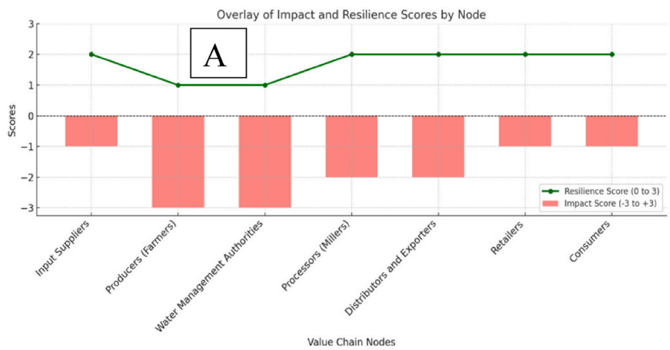
By contrast, trade and policy shocks typically originated downstream and bi-directionally propagated disruption both backwards and forwards within the respective AFVC. Indonesia's palm-oil export ban and India's wheat restriction (Supplementary File 1) triggered global price volatility while simultaneously depressing farm-gate prices and undermining producer confidence (Zaman et al., 2025; USDA, 2025; Brown and Kshirsagar, 2015). The Black Sea blockade similarly exposed the fragility of geographically concentrated trade corridors, disrupting nearly one-third of global wheat exports and disproportionately affecting import-dependent regions (FAO, 2023). In these cases, governance decisions, not biophysical damage at a specific node, determined impact trajectories. Furthermore, a distinct variant emerged in production input-side shocks. Sanctions placed on Russian and Belarusian fertilisers constrained Brazilian maize yields months later (Colussi et al., 2024), demonstrating how embedded input sub-chains can transmit geopolitical shocks directly to farm productivity (Meuwissen et al., 2019). Crucially, impact trajectories diverged sharply both between AFVCs (inter-system variability) and within the similar nodes across different governance and production contexts (intra-system variability). Capital-intensive, vertically integrated AFVCs, such as the US egg production system during the 2022 avian influenza outbreak or Italy's irrigated rice sector, recovered rapidly (as evidenced by the change in impact scores) due to effective response, recovery, and business continuity processes that included biosecurity regimes, insurance, and state support (USDA APHIS, 2022; Patyk et al., 2023). In contrast, smallholder-dominated horizontally fragmented AFVCs in Pakistan and Kenya experienced prolonged disruption due to minimal business

Table 3
Comparative cross-case patterns of shock propagation and resilience outcomes across 12 AFVC cases.

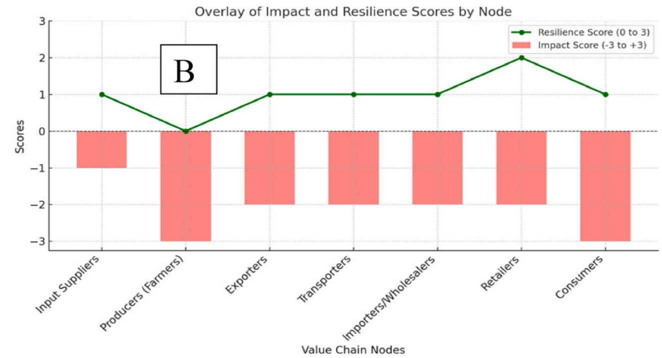
Case Study	Primary Shock Type and Most Vulnerable Node (s)	Observed Propagation Direction	Observed Resilience Outcome	Equity/Distributional Implication
Australia - Wine Grapes Bushfires (2019–20)	Climatic (wildfire) Producers, processors	Forward-propagating (fire damage + smoke taint → lower grape quality → export contract disruptions	Moderate adaptive recovery through insurance uptake and product innovation (Akter and Grafton, 2025; Wine Australia, 2021).	Smaller vineyards faced greater recovery constraints than export-oriented firms with insurance and diversified market access.
Kenya -Sorghum Locust Outbreak (2020)	Biological/ Climatic Producers (smallholders), pastoralists	Forward-propagating (pest swarm → crop destruction → feed scarcity → price inflation)	Anticipatory surveillance and adaptive feed substitution supported recovery (FAO, 2021; WFP, 2020).	Pastoralists and resource-constrained smallholders experienced disproportionate livelihood losses despite external support mechanisms.
Argentina -Beef Export Ban (2021)	Economic (policy shock) Producers & Exporters	Backward-propagating (export restriction → domestic oversupply & price crash → processor income loss → substitution with poultry)	Adaptive recovery through market diversification and Storage expansion (FAO, 2022).	Export-oriented producers experienced income losses despite short-term domestic consumer protection.
India -Wheat Export Ban (2022)	Economic (policy restriction) Exporters, import-dependent buyers (MENA/SSA)	Backward-propagating (export ban → domestic surplus → global deficit → importers' substitution effects)	Adaptive recovery through trade exemptions and strategic reserves (Reuters, 2024; USDA, 2024).	Import-dependent countries faced heightened food insecurity despite domestic market stabilisation within India.
Indonesia - Palm Oil Export Ban (2022)	Economic (trade restriction) Producers (smallholders), exporters	Bidirectional propagation (export ban → domestic supply retention → global edible oil shortage → inflation)	Adaptive recovery through import diversification and price controls. (Reuters, 2022; Shroff et al., 2024; Zaman et al., 2025).	Smallholders experienced market uncertainty while domestic consumers benefited from temporary price stabilisation.
Italy - Rice Drought (2022)	Climatic (heatwave/ drought) Producers (farmers)	Forward-propagating (reduced water flows → lower yields → reduced milling inputs → price rise)	Longer-term adaptive recovery through irrigation reform and drought-resistant varieties (CBI, 2024; ISPRA, 2023).	Larger producers with access to irrigation infrastructure adapted more effectively than smaller farms.
Pakistan – Rice Floods (2022)	Climatic (extreme flooding) Producers (smallholders), local millers	Forward-propagating (production loss → infrastructure collapse (roads, canals, storage) → export chain disruption → income loss)	Low absorptive capacity with prolonged recovery despite emergency support. (Mushtaq et al., 2022; United Nations Development Programme (UNDP)-World Bank and Government of Pakistan, 2022; Qamer et al., 2023).	Smallholders and informal actors experienced disproportionate livelihood losses and delayed recovery trajectories.
Russia-Belarus Fertiliser Sanctions (2022)	Geopolitical (trade sanctions) Producers (farmers), input suppliers	Bidirectional propagation (fertiliser import ban → input scarcity & price surge → reduced yields → profitability loss)	Transformative recovery through stockpiling and input substitution (FAO, 2023; FAO and WTO, 2022; Colussi et al., 2024).	Large agribusinesses adapted more effectively than smaller producers lacking access to alternative inputs.
Suez Canal Coffee -Blockage (2022)	Logistical (infrastructure bottleneck) Importers, roasters, distributors	Forward-propagating (anal closure → shipment delays → stock shortages downstream → market volatility)	Adaptive recovery through logistics rerouting and inventory buffering (ICO, 2021; ITC, 2024).	Smaller importers faced greater cost burdens due to limited logistics flexibility.
Black Sea Ports Blockade (2022–23)	Geopolitical (conflict-related) Exporters (Ukraine) & import-dependent buyers (MENA, SSA)	Bidirectional propagation (port closures → blocked exports → cascading shortages in importing regions → global price surge)	Adaptive recovery through route diversification and alternative sourcing (USDA FAS, 2024; Glauber et al., 2023).	Import-dependent regions experienced heightened food insecurity despite adaptive trade rerouting by exporters.
USA - HPAI Outbreak (2022–23)	Biological (animal disease) Layer farms, processors	Forward-propagating (biosecurity breach → mass culling → supply shortage → price spike)	Adaptive recovery through compensation and enhanced biosecurity (USDA-APHIS, 2023).	Industrial producers recovered more rapidly than smaller operators lacking financial buffers.
Spain Frost-Morocco Floods (2023)	Climatic (frost and rain) Producers (Spain/ Morocco), UK retailers	Forward-propagating (production failure → reduced exports → supermarket rationing → consumer shortage)	Adaptive recovery through protected cultivation and sourcing diversification (DEFRA, 2024; FAO, 2023).	Retailers maintained continuity more effectively than producers facing climatic production losses.

Note: Table 3 provides an empirical comparison of observed disruption pathways, vulnerable nodes, resilience outcomes, and equity implications across the twelve AFVC cases. The table focuses on observed case-study evidence and comparative empirical outcomes, rather than broader conceptual categorisation. Propagation direction refers to whether shocks primarily cascaded forward (upstream → downstream), backward (downstream → upstream), or bidirectionally across interconnected AFVC nodes. Across cases, climatic and biological shocks disproportionately affected upstream production systems, whereas geopolitical and policy shocks generated stronger downstream and bidirectional propagation effects. This empirical comparison informed the broader conceptual typology synthesis presented separately in Table 4.
Table 3 presents an empirical cross-case comparison of how disruptive shocks propagated across AFVCs, which nodes were most vulnerable, the dominant resilience outcomes observed, and the principal equity implications emerging across the twelve cases. Unlike Table 4, which synthesises broader conceptual shock typologies, Table 3 focuses specifically on observed case-study evidence and comparative empirical patterns.

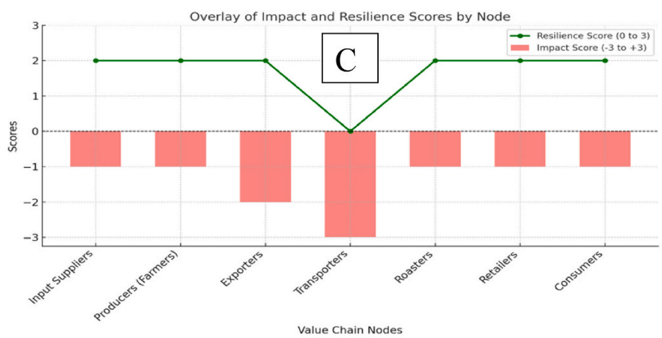
continuity interventions, limited financial buffer capacity, and weak institutional support (Adger et al., 2021; Béné et al., 2023). Overall, the findings reinforce a core principle: vulnerability is produced or enhanced by socio-economic structures. Disruptive shocks may be exogenous, but their consequences are mediated through governance arrangements, market concentration, institutional coordination, and unequal access to adaptive resources. Therefore, longer-term resilience and resolution capacity reside not only in limiting threat exposure alone, but also in reducing the vulnerability associated with unequal access to response, recovery, and adaptive resources, coordination, and decision-making authority across given AFVCs (Folke et al., 2021). In other words, effective response, recovery, and longer-term resolution strategies depend on limiting the node-specific amplification of disruption pathways across AFVCs.



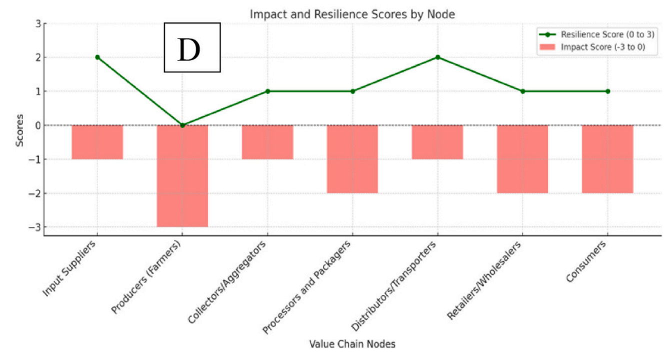
1. Visual Overlay of Node-Specific Impact and Resilience Scores: Italy's Rice Value Chain Under the 2022 Heatwave Across Europe (Source: Author)



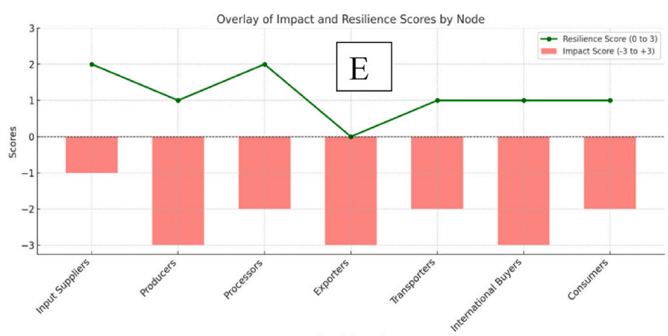
2. Visual Overlay of Node-Specific Impact and Resilience Scores: 2023 Spain's Frost and Morocco's Floods Driven Disruption to the UK Tomato Value Chain (Source: Author)



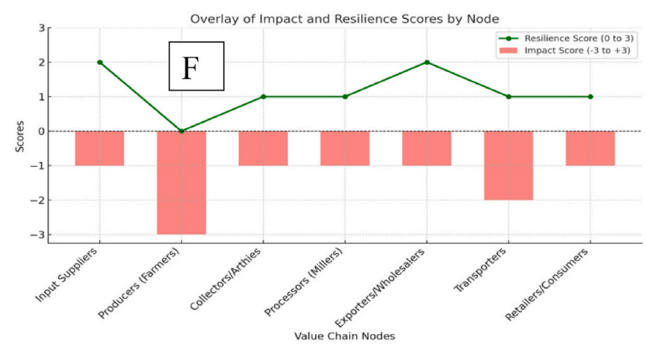
3. Visual Overlay of Node-Specific Impact and Resilience Scores: 2021 Suez Canal Blockade Impact on the EU Coffee Value Chain (Source: Author)



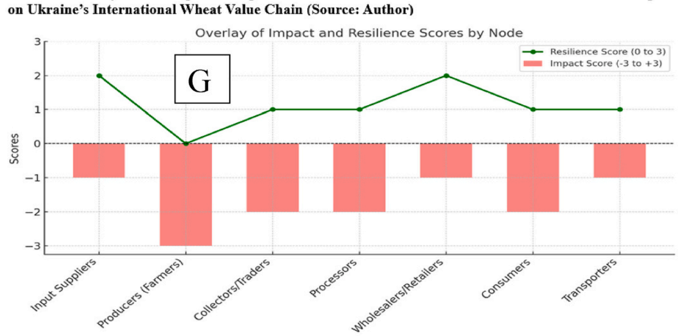
4. Visual Overlay of Node-Specific Impact and Resilience Scores: 2022-23 HPAI A(H5N1) Outbreak Impact on the USA Egg Value Chain (Source: Author)



5. Visual Overlay of Node-Specific Impact and Resilience Scores: 2022 Black Sea Ports Blockade Impact on Ukraine's International Wheat Value Chain (Source: Author)



6. Visual Overlay of Node-Specific Impact and Resilience Scores: Pakistan's Rice Value Chain under the 2022 Floods (Source: Author)



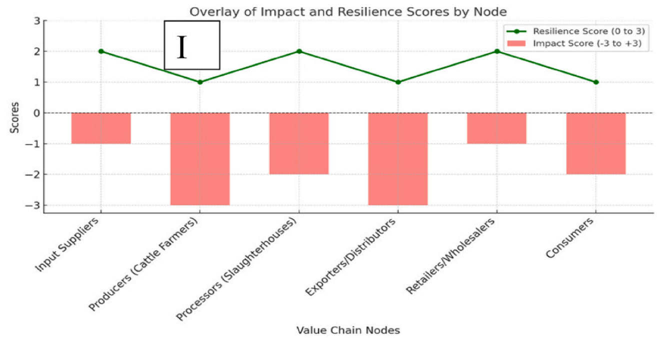
7. Visual Overlay of Node-Specific Impact and Resilience Scores: 2020 Kenya Locust Outbreak Impact on the Country's Sorghum Value Chain (Source: Author)

8. Visual Overlay of Node-Specific Impact and Resilience Scores: 2019-2020 Australian Bushfire Impact on the Country's Wine Grape Value Chain (Author)

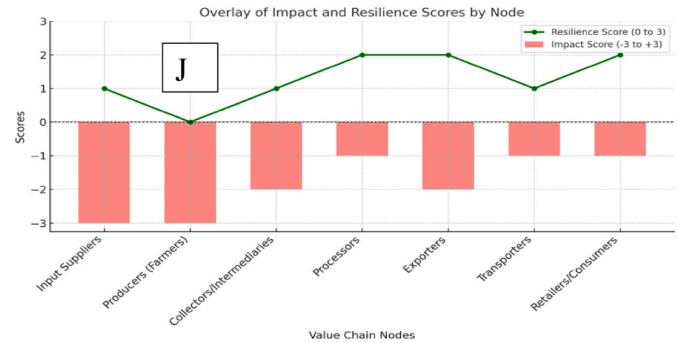
Fig. 2. Collective visualisation of the node-specific dynamics of 12 disruptive shocks case-studies (Sub-figures A-L) (Source: Authors).

5.2. *Shock typologies, impact trajectories and adaptive strategies (RQ2)*

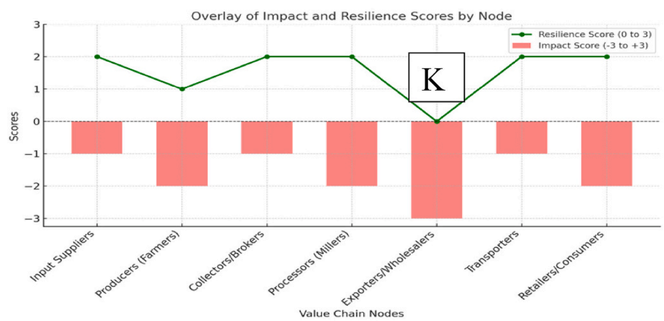
The development of shock typologies is intended to act as a useful framing device when discussing inherently complex and multifaceted case studies, considering a value chain shock is more accurately described as a process rather than an event. Specifically, disruptive shocks cascade across tightly coupled subsystems (production, logistics, markets, and governance), producing multi-directional feedback(s) that either amplify or attenuate impacts depending on system architecture and institutional capacity (de Castro et al., 2025). Pakistan's 2022 floods simultaneously destroyed crops and transport infrastructure, constraining humanitarian relief, input supply, and market access, thereby



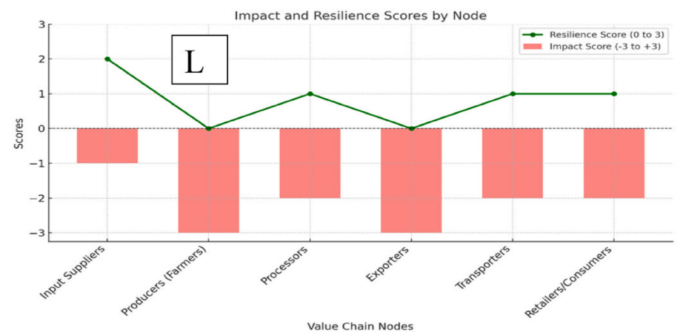
9. Visual Overlay of Node-Specific Impact and Resilience Scores: 2021 Argentina Beef Export Ban Impact on Argentina-China Beef Value Chain (Author)



10. Visual Overlay of Node-Specific Impact and Resilience Scores: 2022 Russia and Belarus Fertiliser Export Sanctions' Impact on Brazilian Maize Value Chain (Author)



11. Visual Overlay of Node-Specific Impact and Resilience Scores: 2022 India Wheat Export Ban's Impact on Global Wheat Supplies (Author)



12. Visual Overlay of Node-Specific Impact and Resilience Scores: 2022 Indonesia Palm Oil Export Ban's Impact on the Global Edible Oil Value Chain (Author)

Fig. 2. (*continued*).

converting production losses into prolonged system-wide disruption (FAO, 2023). Australia's 2019–20 bushfires (Supplementary File 1) further illustrate "dual-node propagation" (Ivanov and Dolgui, 2021), where damage to orchards and vineyards was compounded by subsequent cold-chain breakdowns and labour immobility. These cases exemplify "systemic risk entanglement" (Helbing, 2013), in which interdependent infrastructures and sub-systems transmit stress faster than they can absorb it. Crucially, cascading severity varied by network topology: systems with diversified logistics and infrastructural redundancy, such as Spain's multimodal export hubs, absorbed shocks more effectively than centralised corridors like Ukraine's pre-2022 Odesa route, highlighting governance and investment strategies as the key determinants of resilience (Meuwissen et al., 2019).

The impact trajectories of geopolitical and infrastructural shocks propagated through different channels but exposed similar vulnerabilities. The Black Sea blockade and Suez Canal obstruction revealed the fragility of "just-in-time" trade systems, where even brief interruptions generated long-tail disruptions through inventory depletion and freight-rate escalation (Notteboom et al., 2021). Persistent export backlogs following the partial reopening of Ukrainian ports illustrate temporal amplification, a defining feature of cascading failure (Glauber et al., 2023). Simulation studies corroborate these dynamics, showing that disruptions at highly connected trade nodes produce disproportionate system-wide effects (Ivanov and Dolgui, 2021). This pattern is reflected in our results, where trade-coordination and logistics nodes with high connectivity exhibited some of the highest impact scores and slower recovery trajectories relative to less central nodes. By contrast, more distributed logistics systems, such as Brazil's diversified ports and inland waterways, enabled faster adaptive recovery through enabling redundancy and rerouting, a pattern consistent with higher resilience scores recorded for nodes characterised by infrastructural diversity and alternative routing capacity. Less visible but equally consequential are market-based cascades. The fertiliser shock triggered by Russia-Belarus sanctions transformed a geopolitical disruption into a delayed productivity crisis in Brazil, reducing maize yields and feeding through into higher meat and consumer prices (FAO, 2023). Energy price volatility similarly propagated upstream into fertiliser and transport costs, demonstrating how economic and physical interdependencies operate in tandem (Colussi et al., 2024). In the RIAF results, this pattern corresponded to moderate immediate impact scores but declining resilience over time, as input-dependent production nodes faced rising vulnerability under sustained cost pressures. This illustrates how market shocks can progressively erode adaptive capacity even in the absence of acute physical disruption. The development of typologies considers a broad grouping of descriptive and categorising criteria that demonstrate commonalities and differences across case studies.

Ten disruptive shock typologies emerge from this work, characterised by whether they are initiated by single threat or compound multi-threat incidents, the characteristic impact trajectory, the dominant nodes affected, the response, recovery, and longer-term adaptive mechanisms deployed, and the policy levers of value (Table 3). These ten types of disruptive shock fall into three groups:

Upstream node generated

- Biological/epidemic production collapse (US avian influenza outbreak 2022–23
- Contiguous multi-region supply shocks (2023 Spain/Morocco tomato supply crisis)
- Input supply disruption (Russian/Belarus fertiliser sanctions)
- Production-centric sudden shocks (Pakistan 2022 floods)
- Slow-onset production resource failure (Italian drought 2022)

Midstream node-generated

- Logistics chokepoint/infrastructure failure (blockade incidents)
- Compound socio-technical shock (multi-node systemic shock with strong midstream propagation dynamics)

Downstream node-generated

- Demand side policy shock (import restrictions/tariffs)
- Policy-induced market shocks (trade/export bans)

Table 4
Shock typologies and impact propagation trajectories.

Typology (Short label)	Main impact trajectory (sequence)	Dominant nodes affected	Characteristic timescale	Dominant Resilience Capacity	Representative case(s)	Policy/ managerial levers Indicative Governance Priorities	Key literature
				Upstream node generated			
Biological/ epidemic production collapse	Pathogen/pest spread → mass culling or crop loss → immediate throughput collapse → downstream under-utilisation → price shocks	Producers (bio-dependent) → Processors → Retail/ Consumers	Weeks → years (depends on biological lead times)	Absorptive and anticipatory capacities through surveillance, compensation, and biosecurity systems	USA HPAI (eggs); Kenya locusts (sorghum).	Strengthen surveillance, compensation timeliness, contingency restocking, and biological risk reduction programmes Early-warning systems, coordinated surveillance, compensation mechanisms, and contingency restocking programmes	USDA-APHIS, 2023; Hosseini et al., 2019
Contiguous multi-region supply shock (synchronous supply failure)	Simultaneous shocks across multiple sourcing regions → compounded supply shortfall → downstream acute shortages & market panic	Producers across multiple origin regions → Exporters → Retail/ Consumers	Weeks → season	Adaptive and transformative capacities through sourcing diversification and protected cultivation	Spain/Morocco 2023 (tomatoes to UK); contiguous supply shocks	Develop broader supplier portfolios; incentivise local capacity; invest in protected cultivation; supplier diversification, protected cultivation investment, and strategic sourcing coordination	DEFRA, 2024; FAO, 2023; Zscheischler et al., 2018
Production-centric sudden shock	Extreme event (flood / storm / fire) → direct loss of crop/animals → disruption to local storage & transport → processing bottlenecks → retail shortages	Producers → Collectors → Processors → Transport → Retail	Days → months (medium)	Absorptive and adaptive capacities through emergency relief, temporary reallocation, and insurance mechanisms	Pakistan 2022 floods (rice); Australia 2019–20 bushfires (wine grapes).	Rapid emergency finance; local storage rehabilitation; short-term price supports; invest in on-farm adaptive tech Rapid emergency finance, infrastructure rehabilitation, local storage investment, and adaptive farming technologies	FAO, 2023; Folke et al., 2021
Slow-onset resource failure (	Gradual resource depletion/stress (drought) → constrained irrigation → yield declines over seasons → long-term contraction in output & structural adjustment	Water authorities/ Producers → Processors → Exporters	Months → years (long)	Adaptive and transformative capacities through irrigation reform, water governance, and varietal innovation	Italy 2022 heatwave (Po Basin rice)	Basin governance reform; investment in water-efficient tech; incentives for crop diversification Water governance reform, drought adaptation investment, and crop diversification incentives	Folke et al., 2021; ISPRA, 2023; Colon and Hochrainer-Stigler, 2022
				Midstream node-generated			
Compound socio-technical shock	Multiple drivers (e.g., export restriction during drought) interact → nonlinear amplification → systemic instability across nodes	Multi-node systemic	Multi-scale, long tail	Transformative capacities through integrated governance, cross-sector coordination, and institutional reform	Indonesia palm oil ban + domestic shortages; Pakistan floods + institutional constraints	Integrated policy packages that combine social protection, infrastructure, and market measures Integrated policy coordination, infrastructure investment, and social protection mechanisms	Béné, 2020; Folke et al., 2021; Zscheischler et al., 2018
Logistics chokepoint/ infrastructure failure	Single-point infrastructure failure → immediate halt in flows → global rerouting (longer times, costlier) → inventory depletion downstream → price volatility	Transporters/ Exporters/ Importers → Processors → Retail	Days → weeks (but ripple for months)	Adaptive and redundancy capacities through rerouting, inventory buffering, and multimodal logistics flexibility	Suez Canal / Ever Given (coffee); Black Sea blockade (wheat)	Invest in multimodal redundancy; prioritised corridors for food; contingency contracts and inventory policy Multimodal redundancy, strategic reserves, corridor diversification, and	Notteboom et al., 2021; UNCTAD, 2021

(continued on next page)

Table 4 (*continued*)

Typology (Short label)	Main impact trajectory (sequence)	Dominant nodes affected	Characteristic timescale	Dominant Resilience Capacity	Representative case(s)	Policy/ managerial levers Indicative Governance Priorities	Key literature
						logistics contingency planning	
Downstream node generated							
Demand-side policy shock	Importing country policy (tariffs, stockpiling) or rapid demand shifts → reduced market access for exporters → price & contract failures for producers/exporters	Exporters → Producers → Processors (export-oriented)	Immediate → months	Adaptive capacities through market diversification and contractual flexibility	Argentina beef ban (spillover to China buyers); India wheat ban (importers react)	Improve market diversification, diplomatic engagement, and contract clauses for force majeure Market diversification, trade diplomacy, and adaptive contractual frameworks	Koporcic et al., 2026; Quigley et al., 2020;
Input-supply disruption (global input shock)	External input constraint (fertiliser/ seed/energy) → input price spike & scarcity → reduced yields/ productivity → downstream shortages & inflation	Input suppliers → Producers → Processors/ Exporters	Months → seasons	Redundancy and transformative capacities through stockpiling, supplier diversification, and input substitution	Russia/Belarus fertiliser sanctions → Brazil maize; also relevant for seed/pesticide shocks	Strategic stockpiles; diversify import partners; promote low-input agronomy and domestic production of inputs Strategic stockpiles, diversified sourcing, and low-input agricultural transitions	Da Costa Nunes, 2025; FAO and WTO, 2022
Policy-induced market shock (export bans/ trade restrictions)	Sudden policy closure (ban/restriction) → immediate export market loss → domestic price rebalancing → trade diversion & global shortages	Exporters → Producers → Import-dependent buyers → Consumers	Immediate → months	Absorptive and adaptive capacities through strategic reserves and sourcing diversification	India 2022 wheat ban; Argentina 2021 beef ban; Indonesia 2022 palm oil ban	Transparent policy signalling; phased measures; trade diplomacy; support for producers/exporters Transparent policy signalling, phased interventions, and coordinated trade governance	Koporcic et al., 2026; Quigley et al., 2020;
Product-related shock	Environmental exposure (smoke/ chemical contamination) → quality downgrade → rejection by processors/export markets → reputational & price impacts	Producers → Processors → Exporters → Consumers	Season → years (depending on recovery)	Adaptive and transformative capacities through testing, blending, insurance, and technological innovation	Australia 2019–20 bushfires (wine smoke taint)	Rapid quality testing, blended product strategies, investment in mitigation R&D Rapid quality testing systems, mitigation R&D, and adaptive product management	Akter and Grafton, 2025; Wine Australia, 2021

Notes: Table 4 synthesises the broader propagation archetypes and resilience patterns emerging across the comparative case analysis. The table abstracts empirical findings into transferable conceptual typologies intended to support comparative resilience analysis, anticipatory governance, and policy learning across diverse AFVC contexts. Unlike Table 3, which focuses on observed empirical case-study evidence, Table 4 presents generalised propagation logics and dominant resilience capacities associated with recurring categories of disruptive shocks. To improve readability and reduce duplication, detailed empirical descriptions and extended references have been streamlined or moved to Supplementary Material.
Table 4 synthesises the broader shock archetypes and generalised propagation patterns emerging from the comparative RIAF analysis. Unlike Table 3, which presents empirical case-specific findings, Table 4 abstracts these findings into transferable conceptual typologies and governance-relevant resilience patterns.

- Product-related shock (product recall, panic buying)

Furthermore, the cross-case analysis reveals three broad classes of **propagation directionality** in terms of impact trajectory: (i) forward-propagating (upstream → downstream) climatic shocks (e.g., Pakistan floods, Australian bushfires), (ii) backward-propagating (downstream → upstream) policy and trade shocks (e.g., India's wheat export ban, Indonesia's palm oil ban), and (iii) bidirectional (downstream ↔ upstream) input and price shocks. Fig. 3 illustrates how disruptive shocks propagate across three value chain node positions: upstream (production and inputs), mid-stream (processing and trade coordination), and downstream (distribution, retail, and end markets). Forward propagation is typical of climatic and infrastructure shocks that originate in production systems and cascade through logistics and markets. Backward propagation reflects policy, trade, and demand-side shocks that transmit economic pressures upstream. Bi-directional propagation characterises input, energy, and price shocks that circulate through feedback loops, amplifying system-wide instability and often reinforcing impact (See Fig. 4.)

Each of the above three directionalities operates on distinct time-scales and requires tailored response, recovery, and longer-term resilience strategies rather than generic resilience policies (e.g., fertiliser and energy price crises). These patterns highlight that response, recovery, and resilience interventions must be node-specific, tailored to the dominant impact trajectory rather than designed as uniform policy packages (Distefano et al., 2018). Systems dominated by the risk of forward-propagating climatic shock trajectories require investment in local storage, emergency logistics, and insurance schemes. Those actors exposed to backward-propagating policy shock trajectories need transparent governance and cross-border coordination to mitigate market panic, while bidirectional shock trajectories highlight the need for integrated fiscal, energy, and trade policy coherence (Li et al., 2022).

Overall, this comparative synthesis shows that resilience emerges not as an attribute of individual actors or the resilience strategies at a

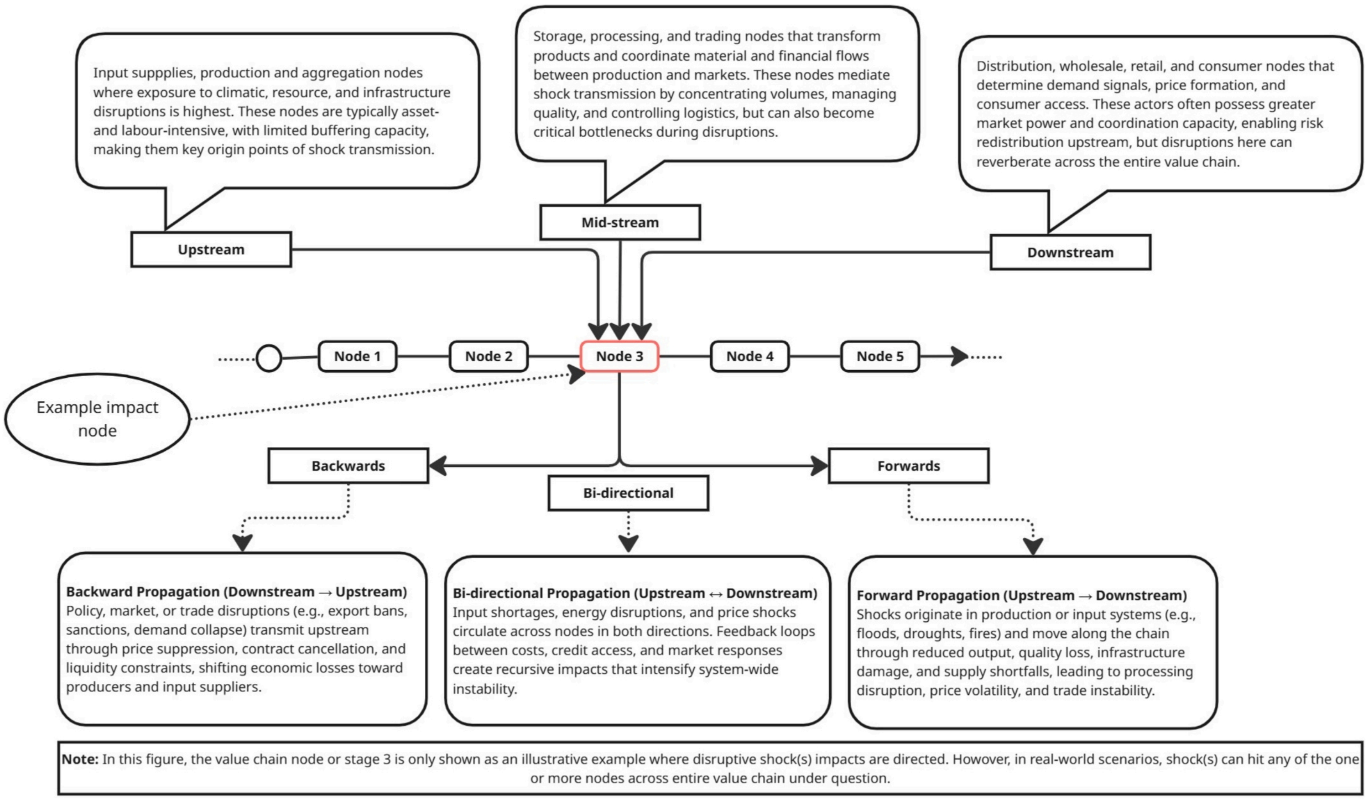


Fig. 3. Directionality and positional dynamics of shock propagation in agri-food value chains (AFVCs) (Source: Authors).

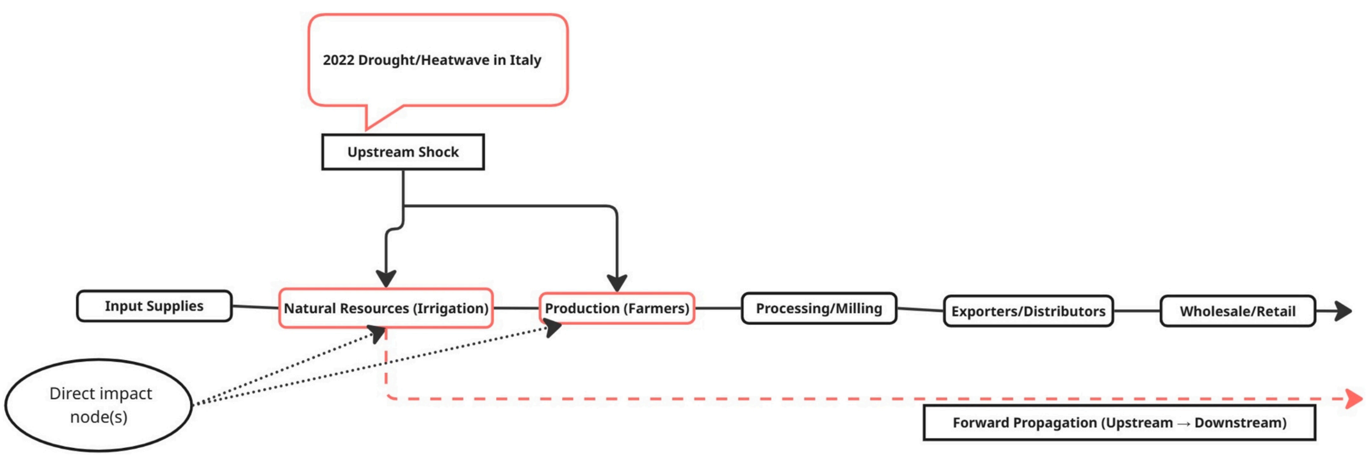


Fig. 4. Illustrative example of the upstream forward propagation shock impact trajectory: the case of the 2022 Italian Drought/Heatwave (Source: Authors).

particular node, but as a property of coordinated networks, shaped by institutional agility, information flows, and social capital (Folke et al., 2021). Preventing cascading of system failure, therefore, depends less on physical infrastructure per se, but rather on how effectively governance systems enable collective adaptive action across interconnected nodes. Here, there is a clear differentiation between collective response, recovery, and adaptive action, and implementing short-term coping strategies that may well leave certain actors vulnerable to the same disruptive shocks should they occur in the future. Whilst considering remediation action in the most vulnerable nodes is important, it may be the case that a different impact type will affect alternative nodes that may otherwise appear unaffected. In which case, a "vulnerable" or "resilient" AFVC is a superposition, depending on how i) each node responds to each shock individually, and ii) how the AFVC responds as a whole.

Adaptive capacity across AFVCs was profoundly asymmetric. Structural redundancy, institutional coordination, and relational flexibility emerged as decisive, reflecting unevenly distributed buffer and adaptive capacity mechanisms (Butler et al., 2021). Systems with diversified sourcing, multimodal transport, and embedded redundancy, such as European importers rerouting Ukrainian grain or retailers diversifying tomato suppliers in the event of supply failure, were better positioned to absorb disruptive shocks. These measures also reflected instances of anticipatory capacity because some actors had invested in preparedness, contingency planning, and alternative routing mechanisms before any disruptions materialised. These cases exemplify "safe-to-fail" design principles, where diversity and redundancy enhanced adaptive capacity and systemic robustness is crucial (de Castro et al., 2025). Yet the ability to invest in redundancy mechanisms, such as maintaining alternative suppliers, backup key resource storage, multimodal logistics routes, emergency inventories, or reserve processing capacity that may never be required, or which downstream actors in the AFVC are not prepared to pay for, remains a challenge for many smallholders, and small and medium sized businesses, especially in low margin supply chains, or where they are price takers rather than price makers embedding resilience-related inequity across AFVCs response, recovery, and resilience architectures. Institutional coordination, in the case examples, determined whether AFVC redundancy translated into effective recovery and longer-term system stabilisation. The U.S. response to avian influenza illustrates how polycentric governance, combining federal indemnities, industry protocols, and real-time data, can accelerate recovery. In contrast, fragmented authority governance and delayed release of recovery funds slowed post-flood recovery in Pakistan and the locust-related response in Kenya.

Relational and contractual flexibility provides a critical buffer capacity where formal adaptive mechanisms either failed or were not available (Distefano et al., 2018). Informal seed sharing, kinship networks, and renegotiated contracts supported short-term response and recovery strategies in Pakistan and Australia. However, flexibility was not universally demonstrated: rigid export contracts and monocultural dependencies constrained adaptive capacity in Argentina and Indonesia. Moreover, some rapid response and recovery mechanisms constituted maladaptive practice, restoring apparent value chain functionality while simultaneously entrenching ecological fragility and social inequity (Hageer, 2025).

A persistent tension across the cases examined lay between implementing coping strategies to ensure system continuity and advancing socio-environmental equity through inclusive adaptation strategies. Many resilience measures prioritised recovering throughput and market stability while externalising costs onto marginal actors and regions with limited capacity to “pass on” such costs (Herrero et al., 2020). Pakistan's post-flood export recovery stabilised foreign exchange earnings but deepened smallholder indebtedness (Iqbal et al., 2024). Europe's supply diversification away from Black Sea wheat protected internal markets yet intensified food insecurity in import-dependent regions of North Africa and the Middle East. Such dynamics resonate with critiques of resilience governance that emphasise functionality over equality and justice (Abdillah et al., 2025). Nonetheless, counter-examples demonstrate that equity and continuity are not inherently incompatible. Community-based locust surveillance in Kenya, targeted seed recovery for flood-affected farmers in Pakistan, and collective water governance in Italy's Po Basin combined functional recovery with social legitimacy. These cases lend empirical support to emerging “just resilience” frameworks that embed participation, redistribution, and environmental stewardship within adaptation strategies (Knox-Hayes et al., 2025).

Governance architectures appeared to mediate resilience outcomes. Vertically integrated regimes (US poultry, EU grains) enabled coordinated recovery through state-industry partnerships (Ciasullo et al., 2022). In contrast, centralised bureaucracies with weak vertical communication, such as Pakistan's provincial-federal interface, generated implementation bottlenecks (Shah et al., 2023). Consequently, the RIAF scoring exposed institutional chokepoints analogous to physical ones: where information silos and rigid budgetary rules delayed resource reallocation even when materials were available (Colon and Hochrainer-Stigler, 2022). Nevertheless, instances of institutional reflexivity also emerged. Kenya's locust-control programme evolved into a regional learning platform under FAO's Desert Locust Resilience Initiative (FAO, 2023). Australia's bushfire-response reforms embedded community co-management and climate-risk planning into agricultural policy (FAO, 2025). Such learning loops illustrate the governance feedback theorised by Folke et al. (2021), whereby crises catalyse organisational learning and policy reform. Cross-case comparison highlighted the need for multi-scalar coordination, linking local innovation with national and transnational governance (Abdillah et al., 2025). In Italy and Spain, EU Common Agricultural Policy instruments facilitated drought-insurance payouts, contrasting with delayed compensation in Argentina and Kenya. Hence, resilience is as much a product of ensuring institutional coherence as of ensuring technological or financial capacity.

5.3. Applicability of the RIAF (RQ3)

The comparative application of the RIAF across 12 AFVC cases demonstrated its analytical value in capturing the differentiated ways disruptive shocks manifest, propagate, the adaptive mechanisms and policy levers deployed, and elucidating the impact trajectories. A central strength of the RIAF lay in its explicit separation of shock intensity from resilience performance, enabling analytical distinction between exposure to disruption and the capacity to anticipate, absorb (coping/robustness capacity), adapt, or transform in response. This distinction moved beyond linear “shock-response” models that dominate food-system risk analysis (Tendall et al., 2015; Béné, 2020) and revealed how similar threats in a given shock type (see Table 3) can produce differentiated impacts given the specific governance structures, resource access, and network configuration of the affected AFVC.

Another key strength was the RIAF's node-based architecture, whereby impact trajectories and adaptive responses can be explored across production, logistics, processing, trade, and retail nodes. This design made visible where any nodes were more vulnerable to disruption than others and demonstrated how disruption was frequently amplified at interconnecting nodes to cause chokepoints. In doing so, the RIAF aligns with complex adaptive systems theory by foregrounding interdependence, feedback(s), and cascading risk (Folke et al., 2021). Importantly, the framework accommodated both material and infrastructural impact (e.g., yield loss, port closure) and institutional dynamics (e.g., export bans, compensation delays), enabling a more holistic rather than reductionist analysis than solely using technical resilience metrics. The RIAF also proved effective as a comparative and heuristic tool, enabling cross-case comparison without erasing contextual specificity. The recoding and triangulation process additionally created opportunities to incorporate diverse expert interpretations, helping reduce subjectivity and refine scoring consistency across cases. The recoding and triangulation process is an opportunity to readily embed diverse expertise in both reducing subjectivity and potentially refining the scoring criteria consistency across cases, although this needs to be undertaken cautiously in order to ensure consistency in scoring logic. Specifically, by applying consistent scoring logic across diverse commodities, geographies, and shock types, the framework facilitated identification of recurring impact trajectories and adaptive mechanisms across diverse settings while retaining sensitivity to local institutional and socio-economic conditions (see Fig. 2). Although potentially subjective (see specific scoring logic per case study in supplementary material), this scoring approach addressed a persistent tension in resilience research between comparability and contextual depth (Béné et al., 2023).

However, several areas for future refinement of the RIAF framework have been observed. Firstly, resilience is dynamic, so integrating additional temporal metrics explicitly (as opposed to within the scoring mechanism) and real-time data would capture impact trajectories and the value of recovery strategies to inform additional anticipatory adaptation. Secondly, equity and inclusion indicators are essential to distinguish functional resilience, which can have a short-term impact (coping strategies), from just resilience, which addresses long-term and often intrenched social inequalities (adaptive strategies) (Hageer, 2025). Thirdly, greater intra-node disaggregation is needed to elucidate heterogeneity among actors in terms of vulnerability and the efficacy and agility of response strategies (both coping and adaptation). Finally, future refinement should enhance temporal sensitivity and anticipatory capacity through real-time data streams, including remote sensing, logistics telemetry, and market indicators, and through coupling with scenario-based simulations or digital twins to stress-test compound shocks (Fanzo et al., 2021).

The comparative analysis herein reinforces the need to conceptualise AFVCs as complex adaptive systems rather than characterising them as linear supply structures. Across the twelve cases, resilience emerged as a relational property shaped by interactions between institutional coordination, network connectivity, and actor diversity, rather than by any single attribute such as efficiency or redundancy (Béné et al., 2023; Folke et al., 2021). Non-linear shock propagation, from local production losses to global price volatility, provides empirical support for multi-scalar and networked models of food-system risk (Tendall et al., 2015; Izquierdo et al., 2022). The methodological contribution of the RIAF lies in advancing a systems-based ontology of resilience that foregrounds interdependence, heterogeneity, and justice as co-constitutive dimensions of stability and recovery (Adger et al., 2021). Methodologically, too, the RIAF demonstrates the value of integrating quantitative exposure metrics with qualitative indicators of adaptive capacity, enabling systematic cross-case comparison while retaining contextual sensitivity, within a flexible mechanism that is not reliant on a specific data source and is not a methodological black box (Hosseini et al., 2019). Indeed, the method is intended to be applied iteratively and ideally revised following a consultation phase. This evidence-synthesis and evaluation architecture addresses persistent limitations in resilience measurement that privilege measurable outputs over relational dynamics such as trust, governance, and information flows (Béné, 2020).

Implications for more effective policy and practice suggest a shift is required from reactive crisis management toward anticipatory resilience governance that extends beyond business continuity planning and instead through active measures such as investments in early-warning systems, strategic redundancy, diversified sourcing, contingency planning, adaptive infrastructure, and cross-scalar coordination mechanisms. Targeted investment in infrastructurally weak nodes and chokepoints could reduce the amplification of shock disruptions, dampen the intensity and course of impact trajectories, and improve coping and adaptive strategies within better coordinated market and regulatory responses, given the characteristics and typology of the particular shock. Despite its comparative breadth, this study has several limitations that warrant critical reflection. Data asymmetry across cases, particularly between high-income and low-income or conflict-affected contexts, shapes both the degree of analytical depth for each case and the epistemic visibility of each situation. While industrialised systems (e.g., EU grain or U.S. poultry) are elucidated by extensive quantitative datasets, conversely, case assessments in smallholder-dominated chains in Pakistan and Kenya rely primarily on qualitative accounts, NGO reporting, and field testimonies. This range of evidence is not readily comparable. This imbalance in spatial, chronological, and data quality granularity across the evidence base reflects a broader structural bias in agri-food resilience research, where informal economies and non-market adaptations remain poorly contextualised and captured (Béné et al., 2023; Scoones and Stirling, 2020). A more inclusive value chain paradigm in which social and natural capital (positive or negative) impacts, following a disruption, are considered more explicitly would require additional scoring mechanisms, but also potentially provide better evidence of the trade-offs and co-benefits inherent in AFVC resilience.

Further, the RIAF framework's node-level aggregation, while enabling systematic cross-case comparison, can obscure nuances in intra-node heterogeneity, especially in cases of an evidence deficit (Petropoulos et al., 2025). At the same time, the structured scoring approach was instrumental in developing the shock typology itself, because quantified impact differentials enabled clearer identification of recurring propagation dynamics, resilience asymmetries, and governance patterns across heterogeneous AFVC cases. Without a comparative impact-scoring framework, distinguishing major structural disruptions from moderate adaptive adjustments would have been considerably more subjective (Hageer, 2025). These disparities reinforce that resilience is socially differentiated, shaped by power, scale, gender, and access to resources (Merkle et al., 2021). Future applications of the RIAF should therefore incorporate intersectional indicators that disaggregate resilience within nodes, rather than treating nodes as homogeneous units. Reliance on secondary evidence sources without appropriate reflexive engagement risks can reproduce technocratic narratives that underplay socio-political contestation (Manning et al., 2020). Integrating participatory and ethnographic data, through applying community-based system dynamics or participatory network mapping, would strengthen the contextual validity and foreground the lived experiences of both deploying ‘sticking plaster’ post-incident coping strategies and engaging in delivering long-term adaptation (Touch et al., 2025). Resilience is not static: short-term coping can evolve into maladaptation or lock-in, so understanding how unlocking strategies can be developed in specific contexts and to deliver pre-defined ‘win-win’ outcomes is important (Manning et al., 2023; Manning, 2024). Therefore, the ability to present the course of multiple impact types in a simple way can support a more nuanced understanding of AFVC functionality. Even a simplified quantification scheme enhances transparency, comparability, and replicability in typology construction, providing an explicit evidential basis for cross-case generalisation (Kc et al., 2025). Longitudinal approaches, drawing on remote sensing, digital traceability, and repeated qualitative engagement, would better capture feedback(s), path dependencies, and delayed effects that can inform future iterations of the RIAF framework (Ivanov and Dolgui, 2021). Extending the framework to incorporate justice, gender, and environmental integrity would move it beyond functional resilience toward assessing transformative capacity, an imperative increasingly recognised in food systems governance (Knox-Hayes et al., 2025).

6. Conclusion

This research advances the understanding of AFVCs' resilience by demonstrating that disruptive shocks are neither isolated nor linear events. Cross-comparing twelve cases, this work finds that disruptive shocks propagate through interdependent AFVC systems via cascading, multi-directional impact trajectories shaped less by the threat itself than by institutional design, network configuration, and uneven actor capacities. In doing so, the analysis challenges dominant technocratic framings of resilience that prioritise efficiency, optimisation, or single-node robustness, and instead positions resilience as an emergent, relational, and politically mediated process (Abdillah et al., 2025) shaped by governance arrangements, institutional coordination, and unequal distributions of absorbative and adaptive capacity across interconnected AFVC nodes. The application of the RIAF demonstrates the value of a more holistic approach to post-hoc resilience assessment. Crucially, the findings reveal that resilience gains in one part of the system may coexist with intensified vulnerability elsewhere, particularly among smallholders, informal actors, and input-dependent producers. Resilience in this case becomes an emergent property, but not an absolute property. The proposal of 10 broad impact types, further distinguishable by impact location (upstream vs downstream node) and impact directionality (forward, backward, or bi-locational), provides a framework for distinguishing and comparing differing impact (and hence resilience) transmission mechanisms. This insight reinforces calls to move beyond perceiving resilience as an example of functional continuity through short-term post-disruption coping mechanisms toward evaluative frameworks that explicitly incorporate relational aspects of resilience, explicitly incorporating reflexive analysis of the influence of inequity, power, and injustice.

At a time of intensifying climatic extremes, geopolitical instability, and market volatility, where disruptive shocks could be more likely, the paper contributes to broader debates by demonstrating that resilience cannot be engineered solely through infrastructure, data, or market response instruments. Rather, resilience within AFVCs depends on governance architectures, how institutions coordinate, how information circulates, and how risks and resources are shared across interconnected systems. Strengthening AFVC resilience, therefore, requires not only the embedding of anticipatory governance and strategic infrastructural redundancy but also deliberate attention to aspects of social differentiation that create vulnerability, improving institutional accountability, and driving long-term transformation. Without such shifts, resilience risks becoming a discourse of technological and policy coping strategies that stabilise fragile systems for a period of time until 'the next time', leaving underlying brittleness that needs to be addressed by fundamental institutional and social adaptation.

CRediT authorship contribution statement

Muhammad Umar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Louise Manning:** Writing – review & editing, Supervision, Conceptualization. **Conor Walsh:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103220.

Data availability

Data will be made available on request.

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