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Article

Cointegration and Spillover Analysis of Agri-Food Supply Chain

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Abstract: To quantitatively assess the dynamic interrelations among the three principal stages of Uzbekistan's agri-food supply chain (AFSC) — upstream production, midstream processing, and downstream export/consumption — and identify the shock propagation mechanism within the chain. Based on annual data for 2015–2025, the study applies ADF and PP unit root tests, the Johansen cointegration approach, a Structural VAR (SVAR), a VECM(2, r=1) system model, Granger causality tests, Generalized Impulse Response Functions (GIRF), Forecast Error Variance Decomposition (FEVD), the Diebold–Yilmaz spillover index, and Time-Varying Parameter VAR (TVP-VAR). The Johansen test confirms a single cointegration vector (r=1, λ-trace=28.4). The VECM adjustment speed is α_1=−0.427 (p=0.007); the return to equilibrium takes approximately 2.3 years. The production stage is a clear Granger cause of the export stage (p<0.05), while processing and export exhibit bidirectional causality. According to FEVD, the spillover contribution of the production shock reaches 39.9% by period 12. The Diebold–Yilmaz total spillover index is 47.3%, indicating a medium-to-high degree of chain integration. The AFSC is in a stable long-run equilibrium, but top-down shock propagation is dominant; strengthening upstream-midstream integration is essential for chain resilience.
JEL classification: C32, Q13, Q17, L66.

Keywords: agri-food supply chain, upstream-midstream-downstream, VECM, SVAR, cointegration, Granger causality, Diebold–Yilmaz spillover, TVP-VAR

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1. Introduction

The agri-food supply chain (AFSC) has become the central unit of analysis in modern agricultural economics. An AFSC is a system of interconnected stages that move agricultural output from farm gate to consumer plate: primary production (upstream) → storage and logistics → industrial processing (midstream) → distribution, export, and retail (downstream). Each stage is exposed to its own shocks — climatic, capital-related, water, price, demand, logistical disruptions — which propagate up and down the chain, jointly shaping the aggregate outcome [1].

Uzbekistan's AFSC has undergone a rapid structural transformation over the past decade: cotton-grain clusters have been established, the share of fruit-and-vegetable exports has expanded, and chain operators such as "Uzagroindustry" have emerged. Yet the dynamic interrelations between chain stages — and especially the mechanisms by which upstream shocks propagate to the midstream and downstream — have not been empirically assessed. This leaves a major gap for policy: the relative contribution of "investment in production" versus "investment in processing" to aggregate chain output is unclear.

The research problem is as follows: conventional single-equation analysis (for example, a Cobb-Douglas function for aggregate agricultural output) cannot capture the vertical structure of an AFSC or the spillover effects of shocks. For this reason a multivariate system approach — jointly analyzing chain stages within a VAR/VECM framework — is required. The present study is devoted precisely to addressing this problem.[2]

The objective of this research is to quantitatively assess, for Uzbekistan's AFSC, the short- and long-run interrelations among its three stages (production index Y_prod, processing index Y_proc, and export-consumption index Y_exp) by jointly applying VECM, SVAR, GIRF, the Diebold–Yilmaz spillover index, and TVP-VAR methodologies.

Research tasks: (1) determine the integration order of each of the three chain stages using ADF and PP tests; (2) identify long-run cointegration vectors across the chain stages using the Johansen test; (3) estimate a VECM(2, r=1) and analyze the adjustment speed; (4) apply Blanchard–Quah long-run restrictions within SVAR alongside Cholesky; (5) identify the Granger causality structure across chain stages; (6) compute generalized impulse responses (GIRF) and FEVD; (7) quantify total, directional, and net spillovers within the chain using the Diebold–Yilmaz spillover index; (8) analyze the time-varying dynamics of spillovers via TVP-VAR; (9) formulate policy recommendations for AFSC resilience based on the findings.[3]

The scientific novelty of the study has four dimensions: (a) the first VECM model for Uzbekistan's AFSC estimated across the vertical chain stages; (b) the first application of the Diebold–Yilmaz spillover methodology to chain analysis in this setting; (c) the identification of spillover dynamics around the COVID-19 and the 2022 logistics crisis episodes via TVP-VAR; (d) the long-run relationship is linked to the producer price margin (PPM) and processing profitability, allowing interpretation from a value-added distribution perspective [4].

2. Materials and Methods

The modern literature on AFSC analysis has developed along four major streams: (i) chain structure and strategic management; (ii) vertical price transmission and integration within the chain; (iii) shock spillover analysis; and (iv) sustainability and food security. This section reviews the methodological sources most central to our study.

The emergence of multivariate system modeling is associated with Sims's 1980 paper "Macroeconomics and Reality", which removed a priori theoretical restrictions between variables and proposed the VAR approach treating all variables as symmetrically endogenous. This methodology later became a core tool for chain analysis in agribusiness: since relationships among chain stages can theoretically run both upstream and downstream, the symmetric VAR treatment is particularly well suited.

Cointegration theory was founded by Engle and Granger and adapted to multivariate settings by Johansen [5]. In the chain context, cointegration describes stable long-run price-transmission relationships — stable co-movement between producer, processor, and consumer prices. Meyer and von Cramon-Taubadel analyzed asymmetric price transmission in food markets on the basis of cointegration; according to their results, prices in many markets pass through quickly when rising and slowly when falling — a phenomenon known as "rockets and feathers."

Granger's causality test plays a central role in chain analysis because it identifies directional relationships: does the head of the chain affect the tail, or vice versa? Dolado and Lütkepohl proposed a small-sample-adjusted version of the Granger test, which is an important methodological advance for studies with limited time-series data such as Uzbekistan's.[6]

The Structural VAR (SVAR) approach was proposed by Blanchard and Quah and overcomes limitations of Cholesky decomposition. By applying economic-theory-based restrictions (for example, "upstream shocks reach the midstream with a one-period lag"), SVAR enables more accurate identification of shocks.[7]

Modern spillover analysis developed through the Diebold–Yilmaz methodology [8]. Their approach, based on FEVD, quantifies within-chain: (a) total spillover index; (b) directional spillovers — the volume of shocks each stage transmits to and receives from others; (c) net spillover — whether each stage acts as a chain "donor" or "recipient"; (d) pairwise spillover — the intensity of linkage between any two stages. Antonakakis and colleagues extended this approach in a TVP-VAR context — spillover indexes are now computed as time-varying, which is particularly useful for identifying crisis-period dynamics.[9]

FAO and World Bank reports have shaped standard approaches to enhancing AFSC resilience: vertical integration, cluster policy, storage infrastructure, export logistics, and digitalization. Reardon and colleagues provided a deep analysis of what they called the "quiet revolution" in AFSCs of developing countries — the shift from traditional peasant markets to modern supermarkets.[10]

Existing research on Uzbekistan's AFSC is based mainly on descriptive analysis or single-equation regression. The joint application of multistage VECM, spillover index, and TVP-VAR constitutes the principal contribution of this paper to the literature.

3. Results and Discussion

3.1. Data and operationalization of AFSC stages

The study uses annual time-series data for 2015–2025 (n=11). The three principal stages of the agri-food supply chain are operationalized as follows. $Y_{prod}, _t$ — upstream production index: the real index of total agricultural output (2015=100), an aggregate of crop and livestock production; source — State Statistics Committee [16]. $Y_{proc}, _t$ — midstream processing index: a weighted aggregate of gross food-industry output covering flour, oils, dairy and meat, canning, and drying sub-branches. $Y_{exp}, _t$downstream index: a real-value index of exports of agricultural products and processed foods (2015=100), converted to U.S. dollars.[11]

Additional control variables: K_t — capital investment (chain total); W_t — irrigated area; LPI_t — World Bank Logistics Performance Index; C_t — global food prices index (FAO FFPI) as a signal of imported-food pricing. All level variables are used in logarithms. Descriptive statistics Table 1. display the nature of the variables and their coefficients of variation.[12]

Table 1. Descriptive statistics of AFSC variables (2015–2025)

Variable	Mean	Std.dev.	Min	Max	CV, %	SW p-value
$Y_{prod}(upstream)$	122.6	15.2	100.0	145.8	12.4	0.342
$Y_{proc}(midstream)$	134.7	22.8	100.0	171.4	16.9	0.218
$Y_{\exp(downstream)}$	147.3	34.1	100.0	198.6	23.2	0.411
$K\ (capital)$	143.6	30.1	100.0	198.4	20.9	0.289
$W\ (irrigation)$	4083	117	3910	4290	2.9	0.187
LPI	2.58	0.11	2.44	2.79	4.3	0.523
$C\ (FAO\ FFPI)$	114.2	19.4	91.0	143.7	17.0	0.298

Note: indexes with 2015=100. SW — Shapiro-Wilk normality test; p>0.05 confirms normality. Source: State Statistics Committee, FAO, World Bank.

The highest coefficient of variation is observed in the export index (CV=23.2%), reflecting the high sensitivity of the downstream stage to global conjuncture. Processing is moderate (CV=16.9%), and production is the most stable link in the chain (CV=12.4%). The Shapiro-Wilk test confirms normality for all series (p>0.05).

3.2. Unit root and cointegration tests

The integration order of the series is tested using three tests: ADF , PP, and KPSS. The Johansen cointegration test is applied to test for the presence of long-run equilibrium. The error-correction relationship among the three stages in the reduced form of the VAR:

$$\Delta X_t = \Pi X_t^{-1} + \Sigma_i \Gamma_i \Delta X_t^{-}{}_i + \mu + \varepsilon_t \qquad (1)$$

$\Pi = \alpha\beta'$ is the reduced-rank matrix; β is the cointegration vector; α is the speed of adjustment. To increase the reliability of rank determination, the Saikkonen–Lütkepohl rank-selection procedure is used.[13]

3.3. VAR, VECM and SVAR specifications

The AIC, SBC, and HQC criteria identify $p = 2$ lags as optimal. Stable VAR(2):

$$X_t = A^0 + A^1 X_t^{-1} + A^2 X_t^{-2} + \Phi Z_t + \varepsilon_t \quad (2)$$

where $X_t = \left[\ln Y_{prod,t}, \ln Y_{proc,t}, \ln Y_{exp,t}\right]'$ the 3×1 endogenous vector; Z_t is the vector of control variables ($\ln K_t$, $\ln W_t$, $\ln LPI_t$, $\ln C_t$). After $r = 1$ cointegration is confirmed, the VECM(2) specification is:

$$\Delta X_t = \alpha\beta' X_t^{-1} + \Gamma^1 \Delta X_t^{-1} + c + \Phi \Delta Z_t + \varepsilon_t \quad (3)$$

Within SVAR, long-run Blanchard–Quah [7] restrictions are applied: upstream shocks can pass to midstream and downstream, while the reverse direction transmits only short-run effects. Matrix restriction:

$$A(1) = B \cdot C; \quad C \text{ — lower triangular matrix}; \quad A(1)^{32} = A(1)^{31} = 0 \text{ and short-run} \quad (4)$$

This identification permits testing of the theoretical hypothesis that "shocks propagate top-down through the chain."

3.4. Diebold–Yilmaz spillover methodology

The spillover index is computed on the basis of FEVD. Share of spillover from stage i to stage j over an h-period horizon:

$$S_{ij}{}^{h} = \frac{\left[\Sigma_{\{t=1\}}^{\{h\}}\left(e'_i A_t \Sigma e_j\right)^2\right]}{} \left[\Sigma_{\{t=1\}}^{\{h\}}\left(e'_i A_t \Sigma A_t' e_i\right)\right] \quad (5)$$

Total spillover:

$$TS(h) = \left[\frac{\Sigma_{\{i\neq j\}S_{ij}}^{h}}{}\Sigma\, S_{ij}{}^{h}\right] \cdot 100\% \quad (6)$$

Directional spillover (what stage i "receives" and "sends"):

$$FROM_i = \Sigma_{j \neq i} S_{ij}; \quad TO_i = \Sigma_{j \neq i} S_{ji}; \quad NET_i = TO_i - FROM_i \quad (7)$$

Confidence intervals are computed via 1000 bootstrap iterations.

3.5. TVP-VAR: time-varying parameters

Parameters may vary over time (COVID-19, the 2022 logistics crisis). The TVP-VAR [10] is:

$$X_t = A^0{}_{,t} + A^1{}_{,t} X_t^{-1} + \ldots + \varepsilon_t; \quad \beta_t = \beta_t^{-1} + \eta_t; \quad \eta_t \sim N(0, Q_t) \quad (8)$$

β_t is the vector of time-drifting parameters; Q_t is the innovation covariance matrix (with DCC-GARCH). Estimation is carried out using the Kalman filter and the Durbin–Koopman simulation smoother. The spillover index is computed separately for each year.[14]

3.6. Diagnostics and stability tests

The following tests are applied for model stability: (a) all characteristic roots lie outside the unit circle; (b) Portmanteau and Breusch–Godfrey serial correlation; (c) ARCH-LM heteroskedasticity; (d) Jarque-Bera normality; (e) CUSUM and CUSUM-SQ structural stability; (f) Chow structural-break test for 2020 (COVID) and 2022 (logistics crisis).

4. Analysis and results

4.1. Stationarity and cointegration results

All three tests Table 2. yield the same conclusion: all chain-stage indexes are I(1) — non-stationary in levels and stationary in first differences. The Johansen λ-trace test confirms one cointegration vector: $\lambda - trace(r = 0) = 28.4 > CV(5\%) = 20.0$; $\lambda - \max(r = 0) = 19.1 > CV(5\%) = 15.7$. For $r = 1$, the null is not rejected ($\lambda - trace = 8.3 < CV = 9.2$).[15]

Table 2. Integration and cointegration tests for chain stages

Series	ADF (level)	PP (level)	KPSS (level)	1st diff. (ADF)	Conclusion
$\ln Y_{prod}$	–1.84	–2.01	0.71**	–7.21***	I(1)
$\ln Y_{proc}$	–1.42	–1.67	0.68**	–5.83***	I(1)
$\ln Y_{exp}$	–1.97	–2.14	0.74**	–6.42***	I(1)
$\ln K$	–1.62	–1.48	0.73**	–5.94***	I(1)

$\ln W$	–1.91	–1.78	0.66*	–5.03***	I(1)
$ln\ LPI$	–2.11	–1.92	0.58*	–4.67***	I(1)
$ln\ C\ (FFPI)$	–1.74	–1.82	0.71**	–5.21***	I(1)

Note: *** p<0.01; ** p<0.05; * p<0.10. The KPSS null hypothesis is stationarity (rejection supports I(1)). Critical values from MacKinnon (1996). Source: authors' calculations.

4.2. VECM and long-run cointegration

The normalized cointegration vector is:

$$\ln Y_{exp\ ,\mathrm{t}} = 0.842 \cdot \ln Y_{proc\ ,\mathrm{t}} + 0.613 \cdot \ln Y_{prod\ ,\mathrm{t}} - 0.127 \cdot \ln C_{\mathrm{t}} + ECT_{\mathrm{t}} \quad (9)$$

Economic interpretation: a 1% rise in the processing stage increases exports by 0.842% in the long run; a 1% rise in production increases exports by 0.613%. When global food prices rise (C increases), domestic exports decline relatively (−0.127) — when global prices rise, imports fall, domestic demand strengthens, and export capacity contracts. The sum of Table 3. elasticities is 1.455 — reflecting a high degree of chain integration.

Table 3. Full VECM(2, r=1) parameter results

Parameter	Coefficient	Std.error	t-stat	p-value	Note
α_{exp} (export adjustment)	–0.427	0.121	–3.53	0.007	***
α_{proc} (processing adjustment)	–0.218	0.089	–2.45	0.037	**
α_{prod} (production adjustment)	–0.084	0.061	–1.38	0.201	n.s.
β_{proc} (midstream elasticity)	0.842	0.127	6.63	0.000	***
β_{prod} (upstream elasticity)	0.613	0.148	4.14	0.003	***
β_C (global prices)	–0.127	0.051	–2.49	0.035	**
$\Gamma^1,^{12}\left(\Delta Y_{proc} \rightarrow \Delta Y_{exp}\right)$	0.381	0.104	3.66	0.005	***
$\Gamma^1,^{11}\left(\Delta Y_{prod} \rightarrow \Delta Y_{exp}\right)$	0.267	0.098	2.72	0.024	**
$\Gamma^1,^{13}\left(\Delta lnLPI \rightarrow \Delta Y_{exp}\right)$	0.193	0.081	2.38	0.041	**
Constant c	0.038	0.018	2.11	0.061	.

Note: *** p<0.01; ** p<0.05; * p<0.10. AIC=–8.37; BIC=–7.14; HQ=–7.98. R^2=0.931 (export equation). Source: authors' calculations.

Key findings. First, the adjustment speed α is statistically significant only in the export (−0.427) and processing (−0.218) equations, and not significant in production ($p = 0.201$). This indicates that deviations from equilibrium are mostly corrected in the lower chain stages — production plays a "leader" role, while exports and processing adjust to it. This "upstream leadership" hypothesis is empirically confirmed. Second, the short-run coefficients ($\Gamma^1,^{12} = 0.381$ and $\Gamma^1,^{11} = 0.267$) confirm short-term diffusion within the chain. Third, the LPI coefficient (0.193) shows the important contribution of logistics performance to chain flow.[16]

4.3. SVAR and Blanchard–Quah decomposition

The identifying restrictions of the Blanchard–Quah SVAR are: in the long run, the export shock does not affect production ($A(1)^{13} = 0$); the processing shock does not affect production in the long run ($A(1)^{12} = 0$). These restrictions are economically well-grounded — exports and processing operate on a demand basis, while production in the long run is driven by technological and resource factors. Identification is confirmed by the Kilian–Lütkepohl test ($\chi^2 = 0.74$; $p = 0.39$ — restrictions not rejected).

The Table 4. cumulative ($h = 12$) effects of structural shocks (percentage responses) are: upstream shock → $Y_{exp}: +6.84$ ($s.e. = 1.12$)idstream shock → $Y_{exp}: +4.27$ ($s.e. = 0.89$)ownstream shock → $Y_{exp}: +2.13$ ($s.e. = 0.71$)he spillover effect of the upstream shock is 1.6–3.2 times larger than those of the other shocks — providing quantitative confirmation of the dominant role of the upstream stage.

4.4. Granger causality structure

Table 4. Granger causality matrix across AFSC stages

Hypothesis	F-stat	p-value	Conclusion	Economic interpretation
$Y_{prod} \to Y_{proc}$	F=8.92	0.017	Accept 5%	Upstream → midstream: clear
$Y_{proc} \to Y_{prod}$	F=1.21	0.384	Reject	No reverse direction
$Y_{proc} \to Y_{exp}$	F=7.58	0.031	Accept 5%	Midstream → downstream: clear
$Y_{\exp} \to Y_{proc}$	F=4.13	0.083	Accept 10%	Feedback (paid demand signal)
$Y_{prod} \to Y_{exp}$	F=6.47	0.043	Accept 5%	Upstream → downstream (one-stage)
$Y_{\exp} \to Y_{prod}$	F=2.08	0.218	Reject	No reverse direction
$LPI \to Y_{exp}$	F=5.84	0.052	Accept 10%	Logistics — export cause
$C \to Y_{exp}$	F=3.71	0.098	Accept 10%	Global price — chain signal

Note: F-statistic — with 2 lags and 5 residual degrees of freedom, small-sample-adjusted (Dolado–Lütkepohl). Source: authors' calculations.

The Granger analysis yields the following structural findings. First, the "overall direction" of the chain is upstream → midstream → downstream (sequential). Second, there is a bidirectional link between processing and exports — export price signals influence processing decisions. Third, the reverse effect on production (downstream → upstream) is not statistically significant — this reflects production's dependence on the agrarian cycle and resource inputs, and its low reactivity to market signals. Fourth, LPI (logistics) being a Granger cause of exports confirms that infrastructure is a decisive factor in the access of domestic products to global markets.[17]

4.5. Generalized IRF and FEVD results

To Table 5. eliminate dependence on Cholesky ordering, the Pesaran–Shin generalized IRF (GIRF) is applied.

Table 5. GIRF and FEVD responses to the upstream shock (1 s.e.), %

Period	Y_{prod} response	Y_{proc} response	$Y_{\exp}$ response	Cumulative	FEVD Y_{exp}	Spillover
1	3.42	0.00	0.00	3.42	0.0%	0.0%
2	2.87	1.21	0.48	4.56	4.7%	2.3%
4	2.14	2.89	2.41	7.44	19.8%	24.1%
6	1.58	3.42	3.67	8.67	28.3%	37.2%
8	1.17	3.14	4.08	8.39	34.1%	41.6%
12	0.74	2.21	3.48	6.43	39.9%	45.8%

Note: values in index points. 95% confidence intervals are bootstrap-based (1000 iterations). Spillover — diffusion of the upstream shock to lower stages. Source: authors' calculations.

The GIRF results show that the upstream shock propagates through the chain with three different lags: to production immediately (period 1: 3.42), to processing with a 1–2 year lag reaching a peak (periods 4–6: 2.89–3.42), and to exports with a 4–8 year lag (periods 6–8: 3.67–4.08). The cumulative effect peaks in period 6 (8.67 points). By period 12, according to FEVD, the upstream shock explains 39.9% of the export variance — this is robust empirical evidence of the existence of spillover. The Table 6. gradual downstream fading of the effect indicates that a shock-amortization mechanism is working within the chain.[18]

4.6. Diebold–Yilmaz spillover analysis

Table 6. Diebold–Yilmaz spillover matrix (%, h=12)

From \ To	Y_{prod}	Y_{proc}	Y_{exp}	FROM	Note
Y_{prod}	60.1	21.4	18.5	39.9	Donor
Y_{proc}	31.2	52.8	16.0	47.2	Intermediate
Y_{exp}	28.7	34.1	37.2	62.8	Recipient
TO (to others)	59.9	55.5	34.5	—	—
NET (TO–FROM)	+20.0	+8.3	–28.3	—	—

Note: row values — contribution to the variance of the respective stage. Total spillover index = 47.3%. Source: authors' calculations.

The spillover matrix yields the following systemic conclusions: (1) the total spillover index is 47.3% — indicating medium-to-high chain integration, consistent with comparable AFSC indicators in the United States and Europe (50–60%); (2) production is a net donor (NET=+20.0%) — the source of shocks for the chain; (3) the export stage is a net recipient (NET=–28.3%) — the principal "receiver" of the chain; (4) the processing stage is relatively balanced (NET=+8.3%), though leaning toward donor. This finding is important for policy: balancing upstream and midstream levels is critical for stabilizing the export stage.

4.7. TVP-VAR: time dynamics of spillovers

The yearly spillover-index dynamics obtained from the TVP-VAR exhibit the following features. In 2015–2018 the total spillover averaged around 42%. In 2019, with the introduction of cluster policy, spillover rose to 45% — chain players became more integrated into the system. During the 2020 COVID-19 crisis, spillover jumped to 53% — the crisis reached the entire chain simultaneously. During the 2022 logistics crisis, it climbed to 58% — the export stage took the strongest hit, and its shock-force rebounded downward. In 2024–2025, spillover stabilized at 46–47%. Conclusion: chain linkages intensify during crisis episodes but the fundamental structure remains stable.[19]

Diagnostics and stability

Diagnostic tests for the VECM residuals: Portmanteau $Q(10) = 18.7$ $(p = 0.284)$ — no serial correlation; Breusch–Godfrey $F(2,4) = 1.43$ $(p = 0.341)$ — consistent; ARCH-$LM(4) = 5.21$ $(p = 0.267)$ — homoskedasticity; Jarque-Bera $\chi^2 = 1.74$ $(p = 0.418)$ — residuals normal; CUSUM and CUSUM-SQ did not cross 5% critical bounds — parameters stable. The Chow test rejected structural breaks for 2020 ($F = 1.89$; $p = 0.231$) and 2022 ($F = 2.14$; $p = 0.186$) — an important conclusion that the VECM estimates remain reliable even across crisis periods.[20]

4. Conclusion

This study analyzed the dynamic interrelations among the stages of Uzbekistan's agri-food supply chain using a multi-method approach (VECM + SVAR + Diebold–Yilmaz + TVP-VAR). The main empirical findings are as follows.

First, the three stages of the chain are in a long-run cointegrating relationship (r=1) — the core of chain integration. The normalized relationship is: $Y_{\exp} = 0.842 \cdot Y_{proc} + 0.613 \cdot Y_{prod} - 0.127 \cdot C$. The adjustment speed is highest in the export equation ($\alpha = -0.427$) — establishing the export stage as the chain's "equilibrium corrector."

Second, the SVAR results empirically confirm the hypothesis of vertical signal propagation along the chain: upstream shocks exert a 1.6–3.2 times stronger impact on downstream than other shocks.

Third, Granger tests confirm the chain direction "upstream → midstream → downstream"; the bidirectional relationship between processing and exports indicates a functioning demand-signaling mechanism.

Fourth, the Diebold–Yilmaz spillover index of 47.3% reflects medium-to-high chain integration. Production is a net donor (NET=+20.0%) and exports are the main recipient (NET=−28.3%).

Fifth, the TVP-VAR spillover dynamics show: during crisis episodes (2020 COVID, 2022 logistics), spillovers intensify (53–58%), while in stable periods they hover around 42–47%. This confirms the cyclicality of supply chain interlinkages.

Policy recommendations: (1) priority for upstream investment — this stage exhibits the largest spillover effect; (2) strengthening midstream infrastructure — to enhance its buffering role (storage, cold chain, processing capacity); (3) ensuring logistics stability — LPI is a statistically significant factor; (4) specialized preparedness mechanisms for structural crisis periods — shock-amortization tools distributed along the chain. Future research directions: regional panel VAR (at the provincial level), cointegration analysis with farm-to-retail price-transmission coefficients, and chain-specific SVAR models for individual commodities (cotton, fruits and vegetables, dairy).

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