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Market integration and price transmission of sorghum in India

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ABSTRACT

Sorghum is one of the major coarse cereals grown worldwide, particularly in semi-arid and rainfed regions, serving as an important source of food, fodder, and biofuel, and providing livelihood support to millions of small and marginal farmers. This study examines the long-run spatial integration and short-run price transmission among five major sorghum producing states in India viz., Maharashtra, Karnataka, Rajasthan, Uttar Pradesh and Tamil Nadu by adopting a set of time-series econometric tools, viz., Augmented Dickey–Fuller (ADF) test, Phillips–Perron (PP) test, Johansen's multivariate co-integration test, Vector Error Correction Model (VECM) and Granger causality test. The data used for the study were from January 2010 to October 2025. The findings from unit-root tests confirmed that all the price series were non-stationary at their levels but became stationary after first differencing, which justified the use of the Johansen co-integration approach. The co-integration shows that strong long-run equilibrium linkage across the major sorghum markets in India. The VECM suggests that Karnataka and Uttar Pradesh bear the main burden of restoring the long-run equilibrium. Granger causality test revealed that bidirectional flow of price is seen between Karnataka and Maharashtra, Rajasthan and Uttar Pradesh, and Uttar Pradesh and Rajasthan states. Maharashtra often leads in setting prices that Rajasthan follows. Tamil Nadu appeared relatively weak in short-run linkages with the rest of the states. However, the study faces challenges related to data limitations and unobserved factors such as policy interventions, transport bottlenecks which may influence the robustness of the estimated market integration and price transmission relationships. Overall, the findings revealed that an efficiently integrated sorghum market system in India with a few dominant and fast-adjusting markets that ensure the dissemination of price signals across regions.

Keywords: *ADF, Granger Causality, Johansen's multivariate co-integration test, Market Integration, long-run spatial integration, Phillips–Perron (PP) test, Short-run price transmission, Sorghum, VECM.*

Introduction

Agriculture remains the backbone of India's economy, supporting livelihoods, ensuring food security, and driving rural development. A large proportion of the rural population still depends on agriculture not only for income but also for employment and nutritional security. In this context, the smooth functioning of agricultural markets is essential, as they play a crucial role in determining how effectively the benefits of production are reached by farmers and consumers. Efficient agricultural markets contribute to price stability, reduce risks and uncertainties, and improve resource allocation, thereby contributing to higher farm incomes and enhanced food security at the national and household levels [1]. Conversely, poorly integrated markets can exacerbate price volatility, weaken price signals and limit the gains from agricultural growth and policy interventions.

In recent years, the idea of *market integration* has emerged as a key indicator of market performance.

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In simple terms, market integration refers to the degree to which prices in different, geographically separated markets change over time [21]. When markets are well integrated, price changes in one market are transmitted fully or partially to other markets, reflecting the presence of arbitrage and efficient flow of information [11]. Under such conditions, regional differences in supply and demand are balanced through trade, by ensuring that both producers and consumers face prices that accurately reflect actual market forces. In contrast, fragmented or poorly integrated markets may display divergent price movements, suggesting the presence of high transaction costs, policy barriers, or infrastructural limitations that hinder effective price transmission [15].

Sorghum is one of the major coarse cereals cultivated globally, particularly in semi-arid and rainfed regions [2] [4] [25]. It plays a dual role, functioning both as a staple food and a vital source of fodder, while also gaining importance in industrial applications such as livestock feed and biofuel production [29]. In India, the leading sorghum-producing states are Maharashtra [18.71 lakh tons), Karnataka (8.16 lakh tons), Rajasthan (5.43 lakh tons), Uttar Pradesh (4.46 lakh tons), and Tamil Nadu (3.80 lakh tons). These states differ substantially in terms of agro-climatic conditions, production practices, market infrastructure, and policy environments. The differences, together with the increasing domestic market integration, shifting trade policies, and changing consumption habits, raise important questions about how efficiently sorghum markets are integrated across regions and how quickly prices respond to market disturbances [13], [16], [18].

In recent decades, India has implemented several market-oriented reforms to enhance agricultural market efficiency. These include amendments to the APMC Acts, the introduction of electronic trading platforms such as e-NAM, and significant investments in rural infrastructure. Despite these initiatives, issues such as price volatility, regional disparities, and inconsistent price transmission persist. For a crop like sorghum, understanding spatial market integration is particularly important because it is predominantly cultivated by small and marginal farmers in resource-limited areas, and it directly influences farm-gate prices, cropping decisions, and income stability.

While several studies [9], [5], [26] [31] have investigated market integration and price transmission for various agricultural commodities in India and other developing countries, using time-series econometric methods such as co-integration analysis, Vector Error Correction Models (VECM), and Granger causality tests. However, existing studies either focus on crops like rice, wheat, and pulses, use relatively short or outdated time periods, or analyze a limited number of markets. Empirical research focusing specifically on sorghum markets remains limited. Furthermore, rapid transformations in market structure, policy environment, and information and communication technologies over the last decade necessitate an updated and rigorous analysis of spatial price relationships in sorghum.

Against this backdrop, the present study was conducted to study the spatial market integration and the nature of price transmission among the major sorghum growing states in India. To capture the degree of interdependence among these markets, the analysis uses modern time-series tools such as Johansen co-integration, Vector Error Correction Models (VECM), and Granger causality tests. Together, these methods make it possible to distinguish long-run equilibrium relationships from short-run price adjustments between key producing and consuming regions. Furthermore, this study aims to generate practical insights for policymakers, particularly on how to strengthen price transmission, enhance market efficiency, and support a sustainable revival of sorghum cultivation in India. By bringing empirical evidence into dialogue with current policy debates, the study adds to ongoing discussions on millet sector reforms, regional crop diversification, and the broader goal of sustainable agricultural development.

Materials and Methods

This study examines spatial market integration in India across five major sorghum growing states, viz., Karnataka, Maharashtra, Rajasthan, Tamil Nadu, and Uttar Pradesh. We have collected the monthly wholesale sorghum prices data from the Agmarknet website [17]. The sample covers the period from January 2010 to October 2025, providing sufficient depth to study both short-run and long-run price movements. Prices are log-transformed prior to estimation so that cointegrating relationships can be interpreted as long-run parity conditions and short-run coefficients as semi-elasticities. A schematic map of the selected study area is provided in Fig. 1 (author's compilation).

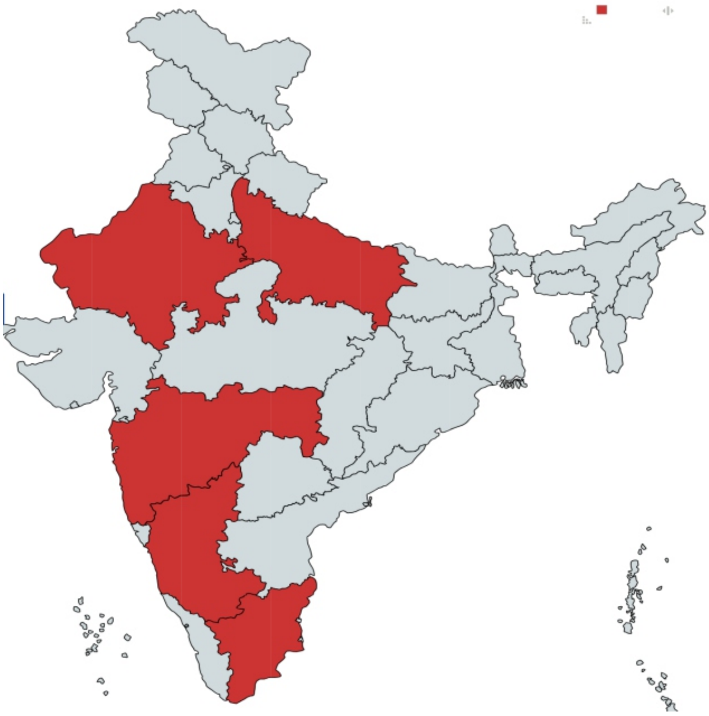

Fig. 1: Selection of study area

Unit root test

Ordinary regressions on non-stationary time series can yield spurious relationships and misleading inference [10]. To study long-run equilibrium among such variables, the appropriate framework is cointegration, which requires that the series be integrated of the same order. We first determine the order of integration for each price series using the Augmented Dickey Fuller (ADF) and Phillips Perron (PP) unit root tests. In the ADF test, the null hypothesis is that the series has a unit root; rejecting the null indicates that the series is stationary [7]. The ADF lag length is chosen to eliminate residual autocorrelation, guided by the Akaike Information Criterion (AIC).

The ADF regression estimated by OLS is:

$$\Delta y_t = \mu + \tau t + \gamma y_{t-1} + \sum_{i=1}^{n} \psi_i \Delta y_{t-i} + \varepsilon_t$$

where μ (and optionally τt) capture deterministic terms, p is the augmentation lag order, and the hypothesis, H0: γ=0, tests for a unit root.

The Phillips-Perron (PP) test provides a complementary check, correcting non-parametrically for serial correlation and heteroskedasticity in εt.

Phillips-Perron (PP) test is given by:

$$\Delta yt=\alpha+\beta t+\gamma yt-1+\varepsilon t$$

where

α is the constant (intercept), β is the coefficient on a linear time trend t (optional), γ tests for a unit root (H0:γ=0), and εt is the error term.

Johnson's co-integration test

Johansen's cointegration test was carried out to find out how many co-integrating relationships are there among the variables or in testing hypothesis about the rank of the co integration space. A level regression was performed to generate residuals which may be thought of as equilibrium pricing errors. Residuals were then subjected to tests for co-integration.

To examine the price relation between states, the following Johnson's co-integration test is used [19], [20].

The Johansen approach starts from a VAR of order *k* in levels:

$$P_{it} = \alpha_0 + \alpha_1 P_{jt} + \varepsilon_t$$

Where, P_{it} is price series of sorghum in i^{th} market at time *t*, P_{jt} is price series of Sorghum in j^{th} market at time *t*, $_0$ is constant that represents domestic transportation costs, processing costs and sales taxes, $_1$ is regression co-efficient which measures the influence of P_{jt} on P_{it}, $_t$ is the residual term assumed to be distributed identically and independently. The test of market integration is straight forward if P_{it} and P_{jt} are stationary variables.

Vector Error Correction Model (VECM)

Once a cointegrating relationship was confirmed between the two-price series, we next estimated a Vector Error Correction Model (VECM) [8]. This model helps us to see how prices react to temporary, short-run shocks and how quickly they move back to their long-run path when they deviate from it.

We start from a general autoregressive distributed lag (ADL) form. The ADL framework provides a convenient way to describe both the immediate (short-run) effects of changes in one variable on another and the eventual (long-run) equilibrium link between them. From this ADL specification, the error-correction form is derived, which includes the "error-correction term" showing the speed at which prices adjust back to equilibrium after a disturbance.

Basic ADL form:

$$Y_t = a_{01} X_t + a_{11} X_{\{t-1\}} + a_{12} Y_{\{t-1\}} + \varepsilon_t$$

Error-correction form for the above:

$$\Delta Y_t = a_{01} \Delta X_t + (1 - a_{12}) [(a_{01} + a_{11}) / (1 - a_{12}) X_{\{t-1\}} + Y_{\{t-1\}}] + \varepsilon_t$$

Generalized form with k lags and an intercept:

$$\Delta Y_t = a_{00} * \sum_{i=o}^{k-1} a_{i1} \Delta X_{\{t-i\}} + \sum_{i=1}^{k-1} a_{i2} \Delta Y_{\{t-i\}} + m_0 (m_1 X_{\{t-k\}} - Y_{\{t-k\}}) + \varepsilon_t$$

Where:

$$m_0 = (1 - \sum_{i=1}^{k} a_{i2})$$

$$m_1 = (\Sigma\_\sum_{i=0}^{k} a_{i1}) / m_0$$

Y_t is the differenced price series in different markets, a_{i1} and a_{i2} are the short-run coefficients. The parameter m_0 measures the rate of adjustment of the short-run deviations towards the long-run equilibrium. Theoretically, this parameter lies between 0 and 1. The value 0 denotes no adjustment, and 1 indicates an instantaneous adjustment. A value between 0 and 1 indicates that any deviation will have a gradual adjustment to the long-run equilibrium values.

Granger Causality Test

Granger (1969) proposed a simple methodology to check whether movements in one time series help to explain movements in another [14]. If we can forecast the present value of a variable Y_t better by adding past values of another variable X_t (over and above the past values of Y_t itself and any other relevant information), then *X* is said to "Granger-cause" *Y*. Likewise, if past values of Y improve the prediction of X_t, then *Y* Granger-causes *X*.

$$Y_i = a_i Y_{t-1} + b_i X_{t-1} + e_i$$
$$X_i = c_i Y_{t-1} + d_i X_{t-1} + v_i$$

This is usually tested by estimating two ordinary least squares (OLS) regressions in which the current value of each variable is regressed on its own lags and on the lags of the other variable. The test is sensitive to how many lagged terms are included, so the appropriate lag length is normally chosen using criteria such as the Akaike Information Criterion (AIC) or the Schwarz Bayesian Criterion (SBC).

Results and Discussion

The sorghum modal price trend of all the selected states is presented in Fig. 2, which shows the asymmetric behaviour in the movement of prices in all the selected states, The maximum modal price of Rs.4753/quintal prevailed in Maharashtra and the minimum price was found in Rajasthan Rs.4112/quintal. The prices of Sorghum remained most volatile in Uttar Pradesh followed by Maharashtra, Karnataka, Tamil Nadu and Rajasthan as measured by coefficient of variation. The highest average prices were found in Maharashtra (Rs. 2309/quintal), while lowest average prices were in Karnataka (Rs. 2003/quintal).

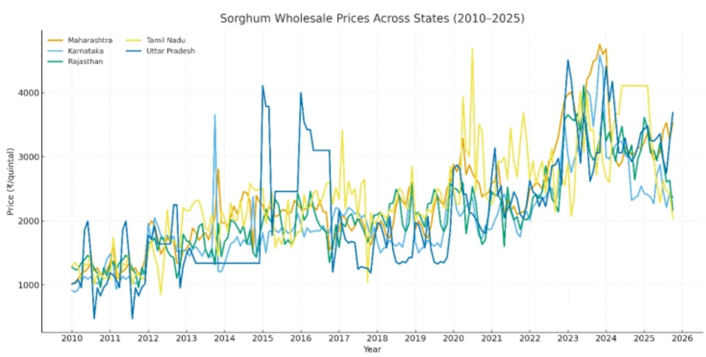

Fig. 2. Price behaviour (Rs./quintal) of Sorghum crop in selected states

Table 1: Summary Statistics of the monthly modal Prices for Sorghum from January, 2010 to October, 2024 (in Rs./quintal)

	Maharashtra	Karnataka	Rajasthan	Tamil Nadu	Uttar Pradesh
MEAN	2309	2003	2120	2360	2154
MEDIAN	2173	1859	2010.5	2297.5	1982
MAXIMUN	4753	4585	4112	4684	4508
MINIMUM	1017	885	957	850	474
STD. DEV.	789.98	675.85	654.47	781.03	898.94
CV	34.21	33.75	30.87	33.09	41.74

Before testing for cointegration, we first diagnose the stochastic properties of each states price series in levels and in first differences.

Order of Integration

Augmented Dickey Fuller (ADF) and Phillips-Perron (PP) test was conducted to check the stationarity of the price series and to determine the order of integration. The unit root test regression implies that regressing the first difference of a series with its one-period lag and several lags (as suggested by the various lag length criteria) of the first differenced series. The null hypothesis of the ADF and PP tests is accepted or rejected based on the critical value and corresponding probability value. It could be inferred from Table 2 that ADF results with intercept and trend fail to reject a unit root in levels for five states, except Uttar Pradesh (stationary at 1% level). From Table 3, Phillips-Perron (PP) test results are also similar, though Tamil Nadu appears stationary at 1% level. After first differencing, all series are stationary in both tests; thus, all the price series of selected states were integrated of order one, I(1), which allowed to proceed with Johansen's co-integration test.

Table 2: ADF test for unit root in the modal prices of sorghum

Augmented Dickey-Fuller test results at the level				Augmented Dickey-Fuller test results after differencing		
	t-statistic	Prob.*	Remarks	t-statistic	Prob.*	Remarks
Karnataka	-2.520228	0.1123	Non-stationary	-13.64471	0.0000	Stationary
Maharashtra	-2.059513	0.2615	Non-stationary	-14.11522	0.0000	Stationary
Rajasthan	-3.162164	0.0239	Non-stationary	-10.2703	0.0000	Stationary
Tamil_Nadu	-2.312398	0.1692	Non-stationary	-15.8578	0.0000	Stationary
Uttar_Pradesh	-3.511824	0.0087	Stationary			

*Notes: * denote significant at 1% level*

Table 3: Phillips-Perron (PP) test for unit root in the modal prices of sorghum

Phillips-Perron test results at level				Phillips-Perron test results after differencing		
	t-statistic	Prob.*	Remarks	t-statistic	Prob.*	Remarks
Karnataka	-3.145428	0.0250	Non-stationary	-28.217	0.0000	Stationary
Maharashtra	-1.831239	0.3645	Non-stationary	-14.80591	0.0000	Stationary
Rajasthan	-3.04275	0.0328	Non-stationary	-39.0619	0.0001	Stationary
Tamil_Nadu	-4.099393	0.0012	Stationary			
Uttar_Pradesh	-3.149156	0.0247	Non-stationary	-19.3604	0.0000	Stationary

*Notes: * denote significance at 1% level*

Johanson co-integration test

Johansen's maximum likelihood co-integration procedure was applied to the monthly prices of the five major sorghum-producing states to examine whether they share a common long-run stochastic trend. The results of both the trace and the maximum eigenvalue statistics are reported in Table 4. For the first hypothesis, there is no co-integrating vector (H_0: r = 0), the trace statistic (304.542) is far higher than its 5 per cent critical value (69.818), and the corresponding p-value is highly significant (p = 0.0001). Similarly, the max-eigen statistic (81.462) also exceeds the 5 per cent level (33.876) with a p-value of 0.0000. Hence, the null of "no co-integration" is rejected in favour of the alternative (r ≥ 1), indicating at least one long-run relationship among sorghum markets.

The same pattern continues for the subsequent restricted hypotheses. When the null is set "at most 1" co-integrating vector (r ≤ 1), both the trace statistic (223.080) and the max-eigen statistic (76.917) remain well above their respective critical values (47.856 and 27.584), with p-values effectively zero, so the null is again rejected and the presence of at least two co-integrating vectors (r ≥ 2) is supported. For "at most 2" (r ≤ 2), the trace statistic rises to 146.162 against a critical value of 29.797, and the max-eigen statistic is 63.517 against 21.131, both highly significant, implying at least three co-integrating relations. Even for "at most 3" (r ≤ 3), the test statistics (trace = 82.64424; max-eigen = 46.12632) exceed the corresponding critical values (15.49471 and 14.26460) with p = 0.0000, so the null is rejected in favour of r ≥ 4. Finally, the hypothesis of "at most 4" (r ≤ 4) is also rejected, since the trace and max-eigen statistics (both 36.51793) are above the 5 per cent critical value (3.841466) with p = 0.0000. Taken together, these results indicate that all successive null hypotheses are rejected up to r = 4, meaning that there exist five co-integrating vectors among the five sorghum market price series. This confirms a strong long-run equilibrium linkage across the major sorghum markets in India, so price movements in one market are not independent in the long run but adjust jointly toward common equilibrium paths. The results are in line with the findings of [6] [22] [24] [28] [30].

Table 4: Johansen's Co-integration Test Results of five major Sorghum Market prices in India

Hypothesized No. of CE(s)	H0	H1	Eigen value	Trace Statistics results			Max-Eigen Statistics results		
				Trace statistics	0.05 Critical Value	P-Value	Max-Eigen Statistic	0.05 Critical Value	P-Value
None *	r =0	r≥1	0.357	304.542	69.818	0.0001*	81.462	33.876	0.0000*
At most 1*	r≤1	r≥2	0.341	223.080	47.856	0.0001*	76.917	27.584	0.0000*
At most 2*	r≤2	r≥3	0.291	146.162	29.797	0.0001*	63.517	21.131	0.0000
At most 3*	r≤3	r≥4	0.221	82.644	15.494	0.0000*	46.126	14.264	0.0000
At most 4*	r≤4	r=5	0.18	36.517	3.8414	0.0000*	36.517	3.841	0.0000

*Notes: in represent the natural logarithm and * denote the rejection of null hypothesis at 1% level of significance*

VECM error-correction

In the long run, the five states were found to move together, so a Vector Error Correction Model (VECM) was fitted to examine the speed at which individual states restore the common equilibrium and to trace short-run price transmission among them. The error-correction term captures the proportion of last month's disequilibrium that is eliminated in the current month. Higher and significant coefficients (in absolute terms) indicate a faster return to equilibrium.

From Table 5, it is clear that Karnataka (−0.9597) and Uttar Pradesh (−1.5304) have negative and highly significant error-correction coefficients, showing that these two states bear the main burden of restoring the long-run equilibrium. This implies that whenever there is a shock to sorghum prices, Karnataka removes almost the entire disequilibrium within about one month, while Uttar Pradesh adjusts even faster and more strongly, pulling the system back to its long-run path. Thus, Karnataka and Uttar Pradesh act as the principal equilibrating centres in the sorghum market system. In contrast, Maharashtra shows a positive and significant coefficient (0.4015), indicating that this state behaves more like a price-originating or leading state in the system rather than a state that absorbs the disequilibrium.

The short-run coefficients also show clear own-market corrections. In the Maharashtra state, the first and second month lagged prices are negative and significant (−0.4041 and −0.2063), which means Maharashtra adjusts about 40 per cent of its own price shock in the first month and a further 21 per cent in the second month. In the Rajasthan state, the first and second months' lagged prices are strongly negative and significant (- −0.6720 at lag 1 and −0.2459 at lag 2), showing that Rajasthan absorbs about 67 per cent of a price shock in the next month and another 25 per cent in the following month.

The Tamil Nadu state shows the strongest self-correction: its own first lagged price is −1.0107, and the second lag is −0.5764, indicating that Tamil Nadu not only fully absorbs the shock within a month but also continues to dampen it in the second month. This confirms that Maharashtra, Rajasthan, and Tamil Nadu prices are strongly influenced by their own monthly lags and quickly converge after a disturbance.

The one-month and two-month lagged prices of Karnataka had large, positive, and highly significant effects on the prices of Uttar Pradesh (1.2303 and 0.5649, respectively) at the 1 per cent level of significance. Similarly, the one-month lagged prices of Maharashtra significantly influenced the prices of Karnataka and Uttar Pradesh by 49.29 and 77.77 per cent, respectively, while the two-month lagged price of Maharashtra significantly influenced the prices of Karnataka by 48.17 per cent. The one-month and two-month lagged prices of Uttar Pradesh also had positive and highly significant effects on the prices of Karnataka by 27.41 and 16.07 per cent, respectively, at the 1 per cent level of significance. In addition, the one-month lagged price of Tamil Nadu significantly influenced the prices of Maharashtra by 8.25 per cent at the 1 per cent level of significance.

The VECM for sorghum prices points to an asymmetric adjustment mechanism. Karnataka and Uttar Pradesh are the fast-adjusting states that restore the long-run equilibrium; Maharashtra mainly plays a price-setting/leading role whose shocks are transmitted to other centres; and Rajasthan and Tamil Nadu mainly stabilize their own short-run fluctuations through strong autoregressive effects. This pattern of a few dominant adjusting markets and several markets with strong own-correction ensures that spatial integration of sorghum prices is ultimately maintained across the major markets in India.

Table 5: Vector Error Correction Model for sorghum prices for five major states in India

Error Correction:	D(KARNATAKA)	D(MAHARASHTRA)	D(RAJASTHAN)	D(UTTAR_PRADESH)	D(TAMIL_NADU)
CointEq1	-0.959713* **[-6.13781]**	0.401514* **[3.91407]**	0.090374 [0.64580]	-1.530414* **[-7.68738]**	-0.075999 [-0.34407]
D (KARNATAKA (-1))	-0.083752 [-0.64239]	-0.028402 [-0.33206]	0.178412 [1.52901]	1.230261* **[7.41135]**	0.057482 [0.31210]
D (KARNATAKA (-2))	-0.15902 [-1.85947]	-0.025004 [-0.44565]	0.087460 [1.14270]	0.564946* **[5.18851]**	-0.068831 [-0.56976]
D (MAHARASHTRA (-1))	-0.492945* **[-3.79632]**	-0.404123* **[-4.74387]**	0.069975 [0.60213]	-0.777704* **[-4.70409]**	0.123184 [0.67156]
D (MAHARASHTRA (-2))	-0.481769* **[-4.51162]**	-0.206326* **[-2.94512]**	-0.061245 [-0.64083]	0.024225 [0.17818]	-0.031189 [-0.20676]
D (RAJASTHAN (-1)	-0.032123 [-0.36250]	0.130438 [2.24365]	-0.671964* **[-8.47277]**	0.281560 [2.49554]	0.183887 [1.46898]
D (RAJASTHAN (-2)	0.016347 [0.19030]	0.131414 [2.33185]	-0.245878* **[-3.19821]**	0.257359 [2.35310]	0.092578 [0.76292]
D (UTTAR_PRADESH (-1)	0.274151* **[3.54211]**	-0.170765* **[-3.36299]**	-0.153418 [-2.21479]	-0.075469 [-0.76584]	-0.009251 [-0.08461]
D (UTTAR_PRADESH (-2)	0.160724* **[2.81506]**	-0.032412 [-0.86530]	-0.025732 [-0.50358]	0.102842 [1.41473]	-0.030673 [-0.38030]
D (TAMIL_NADU (-1)	0.062108 [1.39857]	-0.082591* **[-2.83482]**	-0.067259 [-1.69228]	-0.075962 [-1.34347]	-1.010694 [-16.1110]
D (TAMIL_NADU (-2)	0.032716 [0.73150]	-0.035607 [-1.21349]	-0.075421 [-1.88419]	-0.025788 [-0.45286]	-0.576413* **[-9.12326]**
C	-2.158034 [-0.07996]	0.955857 [0.05398]	-3.03679 [-0.12572]	1.810521 [0.05269]	-1.131147 [-0.02967]

*Note: *denotes significance at 1% level*

Granger Causality Test

The causality test in Table 6 revealed a bidirectional influence of sorghum prices between Karnataka and Maharashtra, Rajasthan and Karnataka and between Uttar Pradesh and Rajasthan, indicating that price signals in these states move in both directions. In other words, a price change in one of these states is quickly reflected in the corresponding partner. In contrast, unidirectional causal relationship was found from Maharashtra to Rajasthan, implying that sorghum prices in Maharashtra lead and influence prices in Rajasthan, but not the other way around. Tamil Nadu, however, appears largely disconnected from the short-run price movements of the other state markets its prices neither help to predict nor are strongly predicted by the rest.

The mixed pattern of bidirectional and unidirectional Granger causality was seen among sorghum markets. These results are in consistent with recent evidence of [3], [23], [27, [32].

Table 6: Pair wise results of the Granger Casualty test

Lagged Periods	Markets Pairs	F-Statistic	P-Value	Decision of null hypothesis	Remarks
1	Maharashtra – Karnataka	2.53196*	0.0306*	Do not reject	Bi-directional
2	Karnataka – Maharashtra	10.3254*	0.00000001*	Do not reject	
3	Rajasthan – Karnataka	2.75677*	0.0201*	Do not reject	Bi-directional
4	Karnataka – Rajasthan	2.28371*	0.0484*	Do not reject	
5	Tamil Nadu – Karnataka	0.42141	0.8334	Reject	No causality
6	Karnataka –Tamil_Nadu	0.98785	0.4267	Reject	No causality
7	Uttar_Pradesh – Karnataka	0.61643	0.6874	Reject	No causality
8	Karnataka – Uttar_Pradesh	0.81492	0.5405	Reject	No causality
10	Rajasthan – Maharashtra	1.696	0.138	Reject	No causality
11	Maharashtra– Rajasthan	2.59425*	0.0273*	Do not reject	Unidirectional
12	Tamil Nadu – Maharashtra	1.02261	0.4059	Reject	No causality
13	Maharashtra –Tamil_Nadu	1.97586	0.0845	Reject	No causality
14	Uttar_Pradesh –Maharashtra	2.04377	0.0748	Reject	No causality
15	Maharashtra– Uttar_Pradesh	2.19769	0.0567	Reject	No causality
16	Tamil Nadu – Rajasthan	0.49544	0.7794	Reject	No causality
17	Rajasthan –Tamil Nadu	1.38054	0.2338	Reject	No causality
18	Uttar Pradesh – Rajasthan	3.01363*	0.0124*	Do not reject	Bi-directional
19	Rajasthan –Uttar Pradesh	6.86057*	0.000007*	Do not reject	
20	Uttar Pradesh – Tamil Nadu	0.53032	0.7531	Reject	No causality
21	Tamil Nadu –Uttar Pradesh	0.5691	0.7236	Reject	No causality

*Notes: * denote significance at 5% level*

Conclusion

This study analysed the spatial integration and price dynamics of major sorghum-producing states in India using monthly modal prices and a system-based co-integration framework. The preliminary ADF and PP unit-root tests showed that, sorghum price series became stationary after first differencing, confirming that the series were integrated of order one, I(1), and suitable for multivariate co-integration analysis. Johansen's maximum-likelihood procedure clearly indicated the presence of multiple (up to five) co-integrating vectors among Maharashtra, Karnataka, Rajasthan, Uttar Pradesh, and Tamil Nadu, implying a strong and stable long-run equilibrium relationship across geographically dispersed markets. The VECM estimates further revealed that Karnataka and Uttar Pradesh are the primary equilibrating centres; these markets absorb most of the short-run disturbances and pull the entire system back to the long-run path within a short period. Granger causality results revealed that bidirectional price transmission between Karnataka and Maharashtra, Rajasthan and Karnataka, and Uttar Pradesh and Rajasthan, alongside a clear unidirectional flow from Maharashtra to Rajasthan, whereas Tamil Nadu remained relatively weak in short-run interlinkages. Overall, the findings suggest that western and northern sorghum markets transmit price information more efficiently than the southern market.

To address these challenges, it is essential to strengthen market infrastructure, particularly in states where prices adjust more slowly, such as Tamil Nadu. Better storage facilities, more decentralized procurement centres, and improved transport networks can help cut down post-harvest losses and support smoother integration of markets. Alongside this, farmers and traders need access to reliable and timely price information. Expanding and upgrading market information systems through mobile-based applications, wider e-NAM coverage, and real-time price dashboards can make their marketing decisions more informed and responsive. Removing hurdles to interstate trade by easing issues like high mandi fees, permit requirements, and logistical bottlenecks would encourage greater movement of grain across state borders, improving competitiveness and helping prices align more closely between regions. At the same time, stronger market linkages through Farmer-Producer Organizations (FPOs), cooperatives, and private aggregators can give small and marginal farmers better bargaining power and access to formal markets. If these structural and policy gaps are addressed in a coordinated way, the sorghum sector can evolve into a more competitive, inclusive, and shock-resilient system supporting both national food security and more stable incomes for millions of sorghum-growing households.

Future scope of the study

Future studies may employ higher-frequency (weekly or daily) price data this will help to see how quickly prices in one market react to changes in another market. Further researchers can directly consider major events, such as government policy changes, market reforms, changes in Minimum Support Price (MSP), trade bans, export/import restrictions, etc. These events often create sudden jumps in price behaviour, so modelling them will give more accurate results.

Conflict of interest

The authors declare that there is no conflict of interest related to the research, authorship, or publication of this article.

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