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Urbanization, Agricultural GDP, and Food Availability in India: ARDL Evidence from 1961–2020

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ABSTRACT

This study investigates the long-run and short-run determinants of food security availability in India using the Food Production Index as a proxy and annual data for 1961–2020. An Autoregressive Distributed Lag (ARDL) bounds-testing approach is employed to estimate cointegration relationships and short-run adjustment dynamics among fertilizer consumption, agricultural GDP, arable land, and urban population. The ARDL results indicate that fertilizer consumption and agricultural GDP are positively and significantly associated with food availability in both the long run and short run, highlighting the importance of input intensification and agricultural sector capacity for sustaining domestic food supply. In contrast, arable land and urban population exhibit significant negative relationships with the Food Production Index in both horizons, suggesting land-related constraints and urban transition pressures on food availability. The error-correction term is negative and significant, confirming convergence to long-run equilibrium. VAR Granger causality tests further show that arable land and urban population contain predictive information for food availability.

1. Introduction

Ensuring food security remains a first-order policy objective in India, not only because of the country's scale and population dynamics but also due to persistent nutrition and access risks that continue to surface in international benchmarks. Food security is widely defined as a condition in which "all people, at all times" have physical and economic access to sufficient, safe, and nutritious food to meet dietary needs for an active and healthy life [8]. Despite long-run agricultural

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modernization and extensive state intervention, India's global performance continues to signal vulnerabilities in food-system resilience and nutrition outcomes. In the Global Food Security Index (GFSI) 2022, India recorded an overall score of 58.9/100 and ranked 68th among 113 countries, indicating continuing exposure to structural risks affecting food availability and stability [7]. Nutrition-related concerns remain salient: the Global Hunger Index (GHI) 2022 ranked India 107th out of 121 countries with a score of 29.1 classified as "serious" [5]. Together, these indicators highlight a central policy tension—how to sustain food availability and resilience in a large, rapidly changing economy facing rising demographic and climatic pressures.

Domestically, the policy stakes are exceptional. India's commitment to food security is institutionalized through one of the world's largest rights-based programmes. The National Food Security Act (NFSA) 2013 provides for coverage of up to 75% of the rural and 50% of the urban population for subsidized foodgrains under the Targeted Public Distribution System (TPDS), equivalent to 81.35 crore persons using the Census 2011 coverage norm[9],[6]. Such extensive coverage reflects strong policy prioritization, but it also implies that fluctuations in domestic production capacity, input availability, and land constraints can generate large welfare consequences, particularly among low-income and nutritionally vulnerable households.

At the same time, India is undergoing a rapid demographic and spatial transition that can reshape food availability through multiple channels. Global projections indicate that the share of the world's population living in urban areas is expected to rise to around 68% by 2050 (United Nations, 2018). For India, the magnitude of urban transition is especially large: official statements drawing on UN projections indicate that hundreds of millions may be added to India's urban population between 2018 and 2050, intensifying pressures on land, infrastructure, and food supply systems [16]. Urban expansion may affect food availability directly through peri-urban land conversion and indirectly through changes in rural labour allocation, food demand concentration in cities, and increased logistical and price pressures in domestic supply chains. These dynamics suggest that food-security planning must be evaluated not only through a sectoral agricultural lens but also through the broader process of structural transformation and urban-transition pressures.

However, macro-econometric evidence that jointly quantifies the long-run and short-run relationships between key production-side determinants of food availability—land capacity, input intensification, agricultural economic performance, and demographic transition—over extended historical horizons remains comparatively limited for India. Much of the existing evidence tends to focus on selected sub-periods, specific drivers, or other food-security pillars (such as access or utilization), leaving less clarity on the combined role of intensification and urban transition in shaping the availability dimension over time. This gap is consequential because policy design requires not only identifying the determinants of food availability but also understanding the speed of adjustment to shocks and the persistence of long-run effects.

This study addresses the gap by estimating an Autoregressive Distributed Lag (ARDL) model for India over 1961–2020, using the Food Production Index as a proxy for the availability pillar of food security. The analysis examines the effects of fertilizer consumption, agricultural GDP, arable land, and urban population on food availability in both the long run and short run. Interpreted through a structural transformation lens, urban population captures urban-transition pressures, agricultural GDP reflects the evolving performance and role of agriculture, while arable land and fertilizer use represent land capacity and intensification needed to sustain output as the economy transforms. The ARDL bounds-testing approach is appropriate for long historical samples and mixed integration orders, and it yields policy-relevant long-run elasticities as well as short-run adjustment dynamics via the error-correction mechanism. The remainder of the paper is organized as follows: Section 2 reviews the literature, Section 3 presents data and methodology, Section 4 reports the results, and Section 5 concludes with policy implications for food-security availability in India.

2. Research Questions

1. Is there a long-run relationship between fertilizer consumption, agricultural GDP, arable land, urban population, and food availability in India?

2. Are there short-run effects of fertilizer consumption, agricultural GDP, arable land, and urban population on food availability in India?

3. Which variables significantly determine food availability in India?

3. Literature Review

Food security is widely understood as a multidimensional concept encompassing availability, access, utilization and stability, with availability referring to the physical presence of food in the economy through domestic production, stocks and trade [8],[4]. In empirical macro studies, the availability pillar is frequently proxied using production-based indicators such as the Food Production Index, which captures changes in aggregate food output over time and is commonly used for cross-country and time-series assessment of production capacity [19]. This production-centred view remains particularly relevant for large developing economies, where availability risks are shaped by the joint evolution of land constraints, input intensification, sector performance and demographic transition.

A substantial body of ARDL-family evidence highlights input intensification, especially fertilizer consumption, as an important driver of production capacity and therefore food availability. District-level panel evidence from Odisha using a PARDL framework shows that fertilizer use improves paddy and sugarcane yields even in the presence of adverse climatic influences, indicating that intensification can partially offset weather-related stresses in crop performance [10]. In a related strand, dynamic ARDL simulation evidence for Nigeria links fertilizer use to cereal production dynamics alongside cropland and labour factors, emphasising fertilizer's role as a productivity-enhancing input within broader supply-side constraints [1]. India-focused evidence using ARDL to assess agricultural inputs similarly finds that fertilizer is among the inputs that support crop output in the long run, reinforcing the role of intensification for sustaining production trajectories [3]. Collectively, these results position fertilizer as a key mechanism through which economies maintain food availability when arable land expansion is limited and production growth must rely increasingly on productivity gains rather than area expansion.

In parallel with input intensification, the literature stresses the importance of agricultural and macroeconomic performance for food availability outcomes. Studies that operationalise food security using production-based proxies suggest that broader economic capacity and sector performance can strengthen food security by enabling greater supply responsiveness and resilience. Evidence for Nigeria employing a QARDL framework with the Food Production Index as a proxy for food security finds that economic expansion is associated with improved food security dynamics across the distribution, highlighting the relevance of macroeconomic conditions for production-based food security outcomes [1]. Additional ARDL evidence focusing on sustainable food security in Nigeria emphasises the role of sectoral capacity in supporting food security performance over time, consistent with a structural transformation interpretation where productivity and sector performance remain central even as economies. These findings motivate the inclusion of agricultural GDP (or agricultural value added) as a key channel capturing the evolving performance of the agricultural sector and its capacity to sustain availability under long-run structural change.

Land capacity constitutes a third foundational determinant in the availability literature. Because agricultural output remains conditioned by the scale and quality of land resources, arable land or agricultural land measures frequently appear as core regressors in ARDL-type models of food security and food production. Evidence from Pakistan using ARDL to model food availability through dietary energy supply and food accessibility through price indices reports that agricultural land is positively associated with both dimensions, highlighting the continuing relevance of land capacity for food security outcomes [17]. In a related production-focused stream, dynamic ARDL simulation results for Nigeria find that cropland is a strong driver of cereal production, suggesting that land availability remains a binding factor for production expansion in contexts where yield growth alone may not fully meet demand pressures. India evidence assessing crop production drivers using ARDL also points to the importance of land-use-related variables and allied agricultural capacity measures in explaining long-run output behaviour [3]. Taken together, this literature suggests that land remains a core structural input for food availability, while simultaneously implying that land constraints heighten the importance of intensification inputs and efficiency improvements.

In contrast, demographic expansion and urbanisation are frequently discussed as structural pressures that can weaken food security by intensifying demand growth and reshaping the agricultural resource base. ARDL evidence for Pakistan focusing on food insecurity indicates that population growth and urbanisation are associated with worsening food insecurity, reinforcing the view that demographic and urban transition can increase vulnerability if production capacity and supply systems do not adjust sufficiently [11]. Related Pakistan evidence that models food availability and accessibility separately finds that urban population growth is linked to weaker food security dimensions, consistent with mechanisms such as peri-urban land conversion, labour reallocation and distributional pressure on supply chains [17]. Evidence from Nigeria using production-based food security proxies similarly reports that population growth can be detrimental to food security dynamics, reflecting demand-side pressures on output expansion and system capacity [1]. This strand of the literature supports treating urban population not merely as a demographic descriptor, but as an indicator of structural transformation pressures that can affect the availability pillar through land, labour and food-system reconfiguration.

Synthesising these strands, ARDL-family evidence indicates that food availability outcomes are shaped by the interaction of intensification inputs such as fertilizer, land capacity such as arable land, agricultural performance such as agricultural GDP, and demographic transition pressures reflected in population and urbanisation. However, the existing evidence often differs in dependent variable choice—ranging from food insecurity indices to dietary energy supply and crop-specific outputs—while some studies are subnational or crop-specific, which complicates inference for a unified national availability proxy over long historical horizon. The present study contributes by integrating fertilizer consumption, agricultural GDP, arable land and urban population within a single ARDL framework for India over 1961–2020, using the Food Production Index as an availability proxy to provide policy-relevant long-run estimates and short-run adjustment dynamics.

4. Data and Methodology

4.1 Data and Variables

The dataset, with 60 observations, was obtained from the World Development Indicator. The dependent variable is Food Production Index, and the independent variables are Fertilizer Consumption, Agricultural GDP, Arable Land and Urban Population. These variables capture the agricultural, technology and demographic dimensions that may influence food security.

4.2 Econometric Specification

To analyze both the short-run and long-run dynamics, we adopt the ARDL model, which allows for the estimation of co-integration relationships among variables of different integration orders (I(0) or I(1)). Additionally, Granger causality tests are employed to assess the directional relationships between variables.

Given that the agricultural and technological variables may influence food security in India, the multivariate equation is expressed as Eq. (1):

$$lnFoodSecurity_t = f(lnfertilizer_t, lnagricultureGDP_t, lnarable_t, lnurban_{t)}) \quad (1)$$

The reduced form of this model is presented as Eq. (2).

$$lnFoodSecurity_t = \alpha + \beta_1 lnfertilizer_t + \beta_2 lnagricultureGDP_t + \beta_3 lnarable_t + \beta_4 lnurban_t + \varepsilon_t \quad (2)$$

where α is the intercept, ε_t is the error term and the parameters $\beta_1 - \beta_6$ signify the estimated coefficients. The signs of the coefficient of β_1 and β_2 are expected to be positive and negative respectively, while the rest of the variables are expected to have a positive sign coefficient (Osabohien, R., Osabuohien, E., & Urhie, E., 2018).

4.3 Econometric Methodology

ARDL model

The ARDL procedure of Pesaran et al. (2001) is utilized to test long-run co-integration among variables. This approach is statistically superior, robust against endogeneity issues, and suitable for variables with different orders of integration, making it advantageous for small sample sizes.

The ARDL model for the underlying variables is as follows:

$$\begin{aligned} \Delta lnFoodSecurity_t &= \alpha_0 \\ &+ \sum_{i=1}^{k} \beta_{1i} \Delta lnFoodSecurity_{t-i} + \sum_{i=0}^{k} \beta_{2i} \Delta lnfertilizer_{t-i} \\ &+ \sum_{i=0}^{k} \beta_{3i} \Delta lnagricultureGDP_{t-i} \end{aligned}$$

$$+\sum_{i=0}^{k}\beta_{4i}\Delta\mathrm{lnarable}_{t-i}+\sum_{i=0}^{k}\beta_{5i}\Delta\mathrm{lnurban}_{t-i}+\beta_{8}lnFoodSecurity_{t-1}+\beta_{9}lnfertilizer_{t-1}+\beta_{10}lnagricultureGDP_{t-1}+\beta_{11}lnarable_{t-1}+\beta_{12}lnurban_{t-1}+\varepsilon_{t} \quad (3)$$

where α is the constant term, Δ is the first difference operator, β_1-β_7 are the coefficients for the short term, while β_8-β_{14} are the coefficients for the long run. The ARDL procedure involves two steps: optimal lag selection using final prediction error (FPE) and an F test to check for long-run relationships among variables. If the F-statistic, compared to [12] critical values, exceeds the upper bound, cointegration is confirmed; if below the lower bound, it's not; intermediate values are inconclusive. After the cointegration of the variables is established, the following estimate of the long-term model is given:

$$\mathrm{lnFoodSecurity}_{t}=\alpha_{0}+\sum_{i=1}^{k}\beta_{1i}lnFoodSecurity_{\mathrm{t-i}}+\sum_{i=0}^{k}\beta_{2i}lnfertilizer_{t-i}+\sum_{i=0}^{k}\beta_{3i}lnagricultureGDP_{t-i}+\sum_{i=0}^{k}\beta_{4i}lnarable_{t-i}+\sum_{i=0}^{k}\beta_{5i}lnurban_{t-i}+\varepsilon_{t} \quad (4)$$

Short-term coefficients are then determined using the error correction model (ECM) in an ARDL technique:

$$\Delta lnFoodSecurity_{t}=\alpha_{0}+\sum_{i=1}^{k}\beta_{1i}\Delta\mathrm{ln}FoodSecurity_{t-i}+\sum_{i=0}^{k}\beta_{2i}\Delta lnertilizer_{t-i}+\sum_{i=0}^{k}\beta_{3i}\Delta\ lnagricultureGDP_{t-i}+\sum_{i=0}^{k}\beta_{4i}\Delta lnarable_{t-i}+\sum_{i=0}^{k}\beta_{5i}\Delta lnurban_{t-i}+\ \theta ETC_{t-1}+\ \varepsilon_{t} \quad (5)$$

Where θ indicates the coefficient of error correction term that represents the adjustment speed and should be significantly negative, ETC_{t-1}, on the other hand, is the lagged error correction term and depicts the length of time it takes for short-term shocks to adapt to their long-term levels. On the other hand, k is the optimum lag based on the information criteria and $dmax$ is the highest degree of integration. The validity of the null hypothesis of no Granger causality is examined using Wald-χ^2 statistics. Equations for other series may be generated similarly.

5. Empirical Results & Discussions

5. 1 VAR Lag Length Criteria

To ensure consistent empirical results, selecting an appropriate lag length for each variable is crucial, especially with fewer than 60 observations. In this study, the VAR model's lag order selection criteria, including the Schwarz Information Criterion (SC) and Hannan-Quinn criterion (HQ), both indicate an optimal lag length of 2.

Table 1
Lag order selection criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	393.5603	NA	8.25e-13	-13.63370	-13.45448	-13.56405
1	838.7746	796.6991	3.27e-19	-28.37805	-27.30276	-27.96016
2	908.7642	112.9658	6.89e-20	-29.95664	-27.98527*	-29.19050*
3	935.4645	38.41087*	6.84e-20*	-30.01630*	-27.14886	-28.90191
4	959.1922	29.97186	7.94e-20	-29.97166	-26.20814	-28.50903

* Indicates lag order selected by the criterion
HQ: Hannan-Quinn information criterion

5.2 ARDL-Bounds Test Result

Table 2 shows the results of bound testing, where the F-statistic (5.7909) exceeds the critical value (5.06) at the 1% significance level. This confirms a significant long-term cointegrating relationship among food production, fertilizer, agriculture GDP, arable land and population in India.

Table 2
ARDL Bounds Test

Test Statistic	Value	k
F-statistic	5.790902	4
Critical Value Bounds		
Significance	I0 Bound	I1 Bound
10%	2.45	3.52
5%	2.86	4.01
2.5%	3.25	4.49
1%	3.74	5.06

5.3 Estimated Long-Run and Short-Run Coefficients and Discussion

Table 3 reports the estimated long-run coefficients from the ARDL model for India, indicating that all explanatory variables are statistically significant. The results suggest that fertilizer consumption contributes positively to food availability (proxied by the Food Production Index). Specifically, a 1% increase in lnFertilizer increases lnFood Production Index by 0.1161%. This finding is consistent with the intensification argument that fertilizer use improves yields and aggregate output capacity, especially when expansion of cultivated area is limited. Similar positive fertilizer–production relationships have been documented in ARDL-family studies such as [10] and []3] where fertilizer use supports agricultural output performance.

Agricultural sector performance, captured by lnAgricultureGDP, also exhibits a positive and significant long-run association with food availability. A 1% increase in lnAgricultureGDP raises lnFood Production Index by 0.2284%. This result supports the view that stronger agricultural economic performance reflects improved sectoral capacity, productivity conditions, and supply responsiveness, which translate into higher long-run food production availability. It is broadly consistent with production-based food security evidence where economic/agricultural performance strengthens availability-oriented indicators over time.

In contrast, arable land (lnArableL) shows a statistically significant negative long-run coefficient. A 1% increase in lnArableL is associated with a 5.257% decline in lnFood Production Index. While this sign differs from the conventional expectation that greater land availability supports output, several structural explanations can rationalize a negative relationship in a long-run macro setting. First, changes in “arable land” over time may reflect shifts toward lower-productivity land, land fragmentation, or land quality deterioration rather than an expansion of effective productive capacity. Second, the long-run negative sign may arise from structural transformation dynamics—where land conversion pressures, degradation, and changes in cropping patterns reduce productivity even when recorded arable land changes only marginally. Third, the magnitude suggests the possibility of scale differences or measurement issues (e.g., definitional changes or multicollinearity with agricultural GDP and fertilizer), implying the need to interpret this coefficient carefully as a macro-association rather than a purely mechanical production function effect. Nonetheless, the estimate signals that land-related dynamics in India are not automatically productivity-enhancing and may be linked to deeper constraints affecting long-run food availability.

Urban population (lnUrbanPopulation) is also statistically significant in the long run and indicates that urbanization exerts a constraining effect on food availability. Interpreting the coefficient together with the negative t-statistic reported in Table 3 and consistent with the short-run estimates in Table 4, the results imply that higher urban population is associated with lower food production availability over the long horizon. This finding is consistent with structural transformation mechanisms whereby rapid urban growth can intensify peri-urban land conversion, alter labor allocation away from agriculture, and increase systemic pressure on domestic supply capacity. It aligns with empirical evidence in the broader food security literature that urbanization and demographic pressures may weaken food security indicators if production capacity and supply systems do not adjust sufficiently (e.g., [17],[10]).

Table 4 presents the short-run dynamics from the ARDL error-correction representation. In the short run, fertilizer consumption remains positive and highly significant: a 1% rise in lnFertilizer increases lnFood Production Index by 0.1655%. This suggests that fertilizer adjustments translate relatively quickly into observable changes in food production availability, consistent with the role of fertilizer as a direct yield-enhancing input. Agricultural GDP also remains positive in the short run (0.1282) and statistically significant, indicating that short-run improvements in agricultural economic performance are associated with immediate gains in food availability, though the magnitude is smaller than the long-run elasticity, as expected under gradual adjustment.

Short-run effects for arable land and urban population are negative and significant. A 1% increase in lnArableLand reduces lnFood Production Index by 2.9516% in the short run, while a 1% increase in lnUrbanPopulation reduces lnFood Production Index by 4.1619%. The short-run negative impact of urban population is consistent with immediate pressures arising from urban expansion—such as land-use conversion at the rural–urban fringe, increased demand concentration, and transitional disruptions in agricultural labor and logistics. The negative short-run arable-land association may similarly reflect transitional land-use dynamics, land fragmentation effects, or compositional shifts toward lower productivity land, rather than an increase in effective cultivated area that raises output.

The error-correction term, CointEq(−1), is negative and statistically significant (−0.5615), confirming convergence to the long-run equilibrium relationship and indicating a moderate speed of adjustment. Specifically, approximately 56% of short-run disequilibrium is corrected within one year, implying that shocks to food availability are partially absorbed relatively quickly, with the remainder adjusting over subsequent periods. This provides policy-relevant insight that supply-side improvements through fertilizer and agricultural performance can influence food availability both immediately and persistently, but structural pressures linked to land dynamics and urban growth can also generate sizeable short-run and long-run constraints.

Finally, the diagnostic tests in Table 3 support model adequacy: the BG-LM test indicates no serial correlation, the Breusch–Pagan–Godfrey test suggests no heteroskedasticity, and the Ramsey RESET test does not indicate functional form misspecification at conventional levels. CUSUM and CUSUM of squares tests show the stability of the model with no specification errors since the plotted lines fall within the stability area, supporting its suitability for policy implications. Overall, the ARDL results suggest that intensification inputs and agricultural performance strengthen India's food availability, while land-related dynamics and urban transition pressures are associated with weaker availability outcomes, underscoring the importance of productivity-led strategies, sustainable land management, and food-system planning under rapid urbanization.

Table 3
ARDL bound test (Long Run) Results

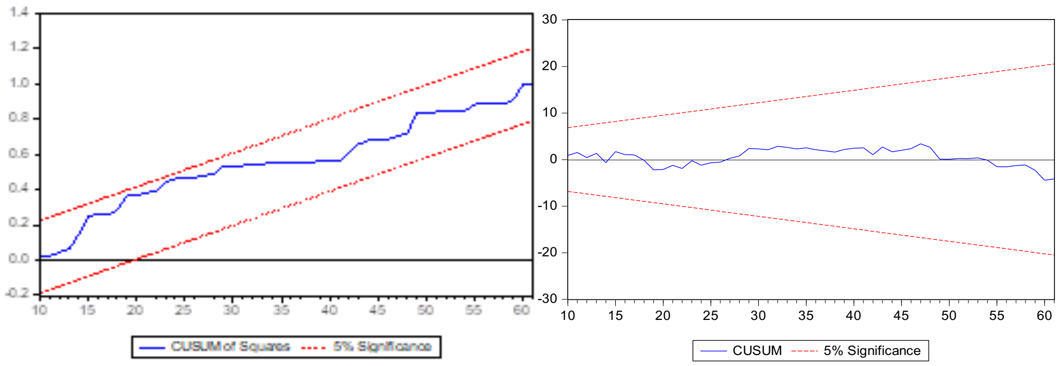
Dependent Variable: lnFoodSecurity		
Lag (1,1,0,0,1)		
Variable	Coefficient	t-stat
lnFertilizer	0.1161***	2.6863
lnagricultureGDP	0.2284**	2.5040
lnarableL	-5.257***	-5.666
lnurban	-2.2924***	-8.4056
C	94.6852***	5.309
Diagnostic Test	F- stat	p-value
BG-LM	0.0294	0.9710
Breusch-Pagan-Godfrey	1.0121	0.4337
Ramsey-RESET	2.1023	0.1532

Note: The asterisk ***, **, and * represent levels of significance at 1%, 5, and 10% respectively.

Table 4
ARDL bound test (Short Run) Results

Dependent Variable: lnFoodSecurity		
Lag (1,1,0,0,0,0)		
Variable	Coefficient	t-stat
lnFertilizer	0.1655***	3.6812
lnAgricultureGDP	0.1282***	2.7483
	-	-4.6481
lnarable	2.9516***	
	-	-2.4943
lnurban	4.1619***	
	-	-5.6680
CointEq(-1)	0.5615***	

Note: The asterisk ***, **, and * represent the levels of significance at 1%, 5%, and 10% respectively.



5.4 VAR Granger Causality/Block Exogeneity Wald Tests

Table 5 reports the VAR Granger causality/Block Exogeneity Wald test results with lnFood Production Index as the dependent variable. The findings indicate that lagged fertilizer consumption and agricultural GDP do not Granger-cause the food production index at conventional significance levels (p = 0.1416 and p = 0.3810, respectively). In contrast, arable land and urban population exhibit statistically significant predictive causality toward the food production index, with p-values of 0.0120 and 0.0002, respectively. The joint block exogeneity test is also significant (p = 0.0012), implying that the set of regressors is collectively informative for predicting movements in India's food production index within the VAR framework. Overall, the evidence suggests that changes in land dynamics and urban transition pressures contain stronger predictive content for food availability than fertilizer use and agricultural GDP in the short-run VAR setting.

Although lnFertilizer and lnAgricultureGDP are statistically significant in the ARDL estimates (in the long run and/or short run), the VAR Granger causality tests indicate that neither variable provides additional short-run predictive content for lnFood Production Index within the VAR system. This divergence is plausible because the ARDL framework captures long-run equilibrium relationships and adjustment dynamics through the error-correction mechanism, whereas Granger causality in a VAR evaluates whether lagged values improve short-run forecasting beyond the information contained in other lags; the result can also be sensitive to the chosen lag length and overlap in information across regressors (multicollinearity).

Table 5
Granger causality test/Block Exogeneity Wald Tests
Dependent Variable: *lnFoodSecurity*

Excluded	Chi-sq	df	Prob.
lnfertilizer	3.910054	2	0.1416
lnagricultureGDP	1.929975	2	0.3810
lnarable	8.843244	2	0.0120
lnurban	17.52044	2	0.0002
All	25.57018	8	0.0012

Note: The asterisk ***, **, and * represent the levels of significance at 1%, 5%, and 10% respectively.

6. Conclusion

This study examined the determinants of India's food-security availability using the Food Production Index as a proxy and estimating an ARDL model over 1961–2020. The results indicate that production-side intensification and agricultural sector performance remain important for sustaining food availability. Fertilizer consumption and agricultural GDP are both positively and statistically associated with the Food Production Index in the long run, and they also display positive short-run effects, implying that improvements in input use and agricultural performance can translate into both immediate and persistent gains in food availability.

In contrast, the estimates show that arable land and urban population are negatively associated with the Food Production Index in both the long run and the short run. This pattern suggests that land-related dynamics and urban-transition pressures may be constraining food availability, potentially through mechanisms such as land quality decline, fragmentation, peri-urban conversion, and factor reallocation away from agriculture. The error-correction term is negative and significant, indicating convergence to long-run equilibrium; the estimated adjustment speed implies that a substantial share of short-run deviations is corrected within a year, highlighting meaningful but not instantaneous adjustment in India's food availability system.

The VAR Granger causality/block exogeneity tests complement these findings by showing that arable land and urban population contain predictive content for movements in the Food Production Index, whereas fertilizer consumption and agricultural GDP do not Granger-cause the index within the VAR setting. This divergence is consistent with the interpretation that fertilizer and agricultural performance are structurally important in the ARDL long-run relationship, while land and urbanization pressures may dominate short-run predictive dynamics in the multivariate VAR framework.

6. Policy Implications

There are several policy implications follow from the findings. First, the positive role of fertilizer consumption supports the case for sustaining productivity-oriented intensification, but with a strong emphasis on efficiency and sustainability. India should strengthen soil-testing and balanced nutrient management, promote precision application (right source, right rate, right time, right place), and scale soil-health monitoring so that fertilizer-driven productivity gains do not come at the cost of soil degradation or water contamination. Improving fertilizer-use efficiency can deliver "more output per unit input," which is crucial when land expansion is limited.

Second, the positive association between agricultural GDP and food availability implies that policies raising agricultural productivity and resilience remain central to food-security planning. This includes continued investment in agricultural R&D, extension services, irrigation reliability, climate-resilient seeds, mechanization appropriate for smallholders, and post-harvest systems that reduce losses. Strengthening market linkages and reducing transaction costs can also support higher farm incomes and productive reinvestment, reinforcing the agricultural-performance channel.

Third, the negative relationship between arable land and food availability indicates that land quantity alone is not guaranteeing higher output—suggesting a need to prioritize land quality, land governance, and sustainable land management. Policy should focus on preventing degradation, improving soil organic content, managing salinity and erosion, addressing fragmentation constraints where feasible (through cooperative farming models or land-lease market improvements), and safeguarding high-quality agricultural land from unplanned conversion. The aim is to protect "effective arable land" which is land that is not only classified as arable but remains productive and sustainably managed.

Fourth, the negative effect of urban population highlights the urgency of integrating food-security planning with urbanization strategy. Urban expansion should be guided toward land-use planning that limits conversion of high-productivity peri-urban farmland and improves rural–urban supply-chain efficiency. Investments in logistics, storage, cold chains, wholesale markets, and transport connectivity can reduce the friction of feeding rapidly growing cities without undermining production incentives. Strengthening urban food-system planning, especially for staples distribution and price stabilization can also mitigate transitional pressures associated with demographic shifts.

Finally, the Granger causality evidence suggests that land and urban-transition variables may provide early signals for changes in food availability. Policymakers may therefore benefit from building monitoring dashboards that track peri-urban land conversion, cropping patterns, land productivity metrics, and urban growth pressures alongside production and input indicators. Such an approach can improve anticipatory policy responses, especially where food availability is sensitive to structural shifts rather than only to annual input changes**.**

7. Limitations And Directions For Future Research

This study focuses on the availability pillar using a national production index and a parsimonious set of determinants. Future work could extend the analysis by incorporating explicit climate variables, irrigation intensity, technology adoption measures, and trade/stock channels, as well as testing for structural breaks and non-linearities that may arise under rapid urbanization and changing policy regimes. Disaggregated analysis across regions or major crops could also clarify whether the negative land and urbanization associations are driven by specific states, land-quality dynamics, or shifting crop composition.

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