

Article

Trends and Factors Affecting Consumption of Fertilizer in Australia: The Moderating Role of Agri R&D Investment

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Abstract: The Australian agriculture sector currently relies on imported fertilizers, which poses risks to price stability and increases the potential for supply chain disruptions. This study aims to investigate the trends and factors affecting fertilizer consumption in Australia, considering the moderating effects of agricultural GDP and agri R&D expenditure. The econometric models, including ARDL bound tests, Granger causality tests, and FMOLS, were used to analyze quarterly data from 2000 to 2023. The findings confirm that a significant long-run relationship exists among the variables of crop production, agricultural export–import ratio, and agricultural R&D expenditure. The moderating effects of agricultural GDP and agricultural R&D expenditure on fertilizer consumption were also found to be significant. The Granger causality test results indicate that bidirectional causality exists between agricultural GDP and fertilizer consumption, arable land and fertilizer consumption, employment and fertilizer consumption, and the export–import ratio and fertilizer consumption. The findings from the robustness checks confirm that most of the variables are co-integrated with fertilizer consumption, except agri GDP and employment. Thus, policymakers are advised to prioritize investment in agricultural R&D to promote sustainable fertilizer consumption and enhance agricultural value addition in Australia.



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Keywords: agri R&D; fertilizers consumption; ARDL; agri export/import ratio

1. Introduction

The global demand for food has led to significant changes in agricultural technology, production methods, and the use of inputs to enhance agricultural productivity. Ref. [1] pioneered the argument regarding how technological innovations in fertilizers affect agricultural productivity and shape market dynamics. Refs. [2,3] illuminated the biological revolution in fertilizer production that followed the mechanization revolution of the 1930s and 1940s. These developments have resulted in farmers increasingly utilizing fertilizers to boost agricultural production and ensure global food security.

The global fertilizer market was valued at approximately USD 212.8 billion in 2023, and is estimated to reach USD 541.20 billion by the end of 2030 [4], with a compound annual growth rate of 5.99%. Demand for fertilizers is primarily driven by field crops, spurred by population growth and rising global food consumption [5,6]. Nitrogen-based fertilizers hold the largest market share, followed by Phosphorus and Potassium. The Asia-Pacific region is projected to capture a significant portion of the market, supported by government initiatives for small and marginal farmers in food crop production [7,8]. In North America and Europe, advanced technology, steady growth, and high per capita

fertilizer consumption are driving the markets, with the U.S. and Canada as primary contributors in North America, while Germany and France lead in Europe. The Middle East and Africa are expected to experience the fastest growth in fertilizer consumption due to rapid population growth, increased investment in agricultural infrastructure, and a focus on food security [9]. The Australian fertilizers market is elaborated and compared using a three-dimensional analysis of time series data. Figures 1 and 2 provide details of NPK fertilizer production and consumption in Australia. In Figure 2, we observe that Australia has a significant portion of fertilizer consumption, though it produces only half of the amount consumed locally. Figure 3 shows the NPK fertilizer export-to-import ratio in the context of Australia, which is the key striking point of this study.

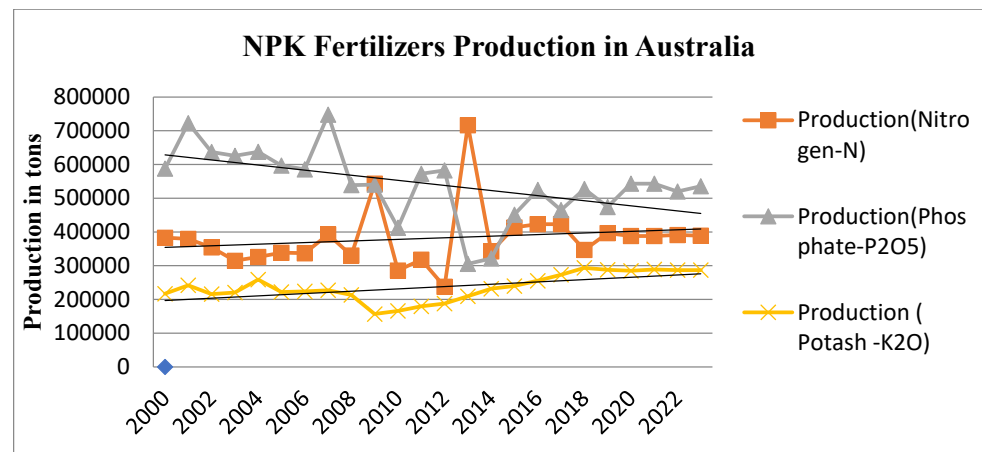


Figure 1. Trends in NPK fertilizer production in Australia, 2000–2023 (source: ABS).

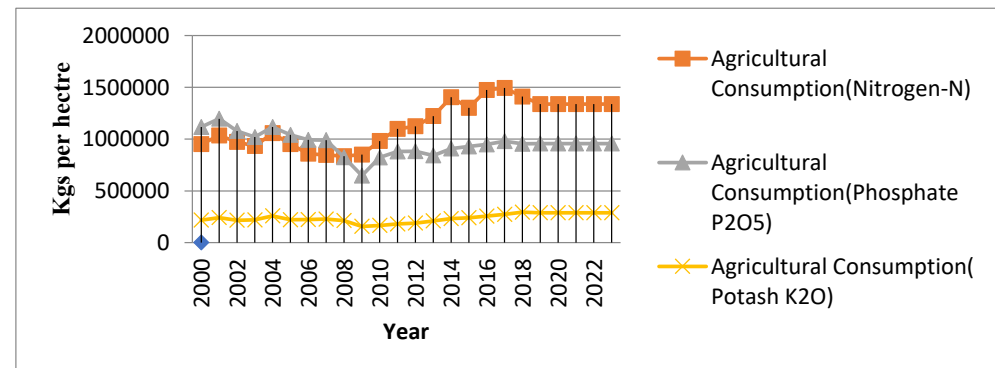


Figure 2. Trends in NPK Fertilizer agricultural consumption in Australia, 2000–2023 (source: ABS).

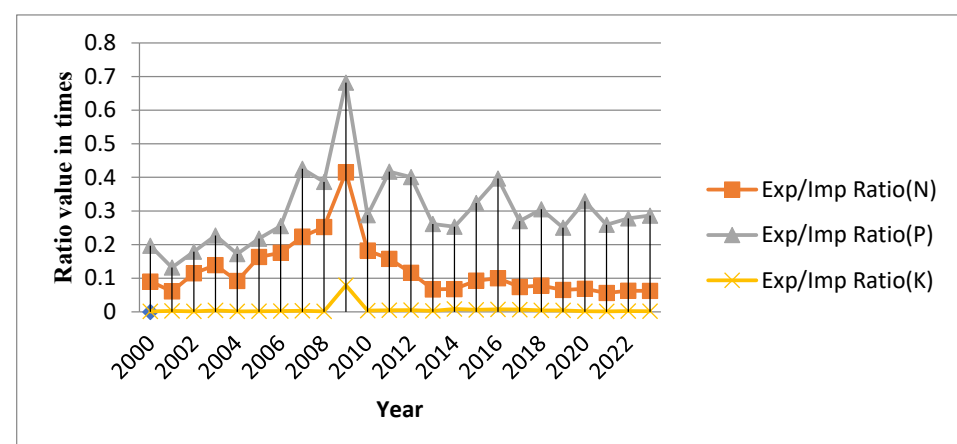


Figure 3. Trends of export–import ratio of fertilizers in Australia, 2000–2023 (source: ABS).

Fertilizers contain essential nutrients such as Phosphorus, Nitrogen, Potassium, sulfur, concentrated nutrient blends, and essential trace elements. Annually, between 6.0 and 7.0 million tons of fertilizers are used in agricultural production, but only about half of this volume is produced locally; the rest is imported (Figures 2 and 3). This reliance on imports exposes the industry to vulnerabilities in global supply chains, with limited control over pricing. Recent events, such as the COVID-19 pandemic, the European natural gas crisis, and the Russia–Ukraine conflict, have severely impacted global fertilizer supply chains, leading to significant price increases affecting the Australian fertilizer market [7]. Moreover, these disruptions have heightened concerns about Australia’s dependence on imported fertilizers. Raw materials such as sulfur and phosphate rock, used to produce superphosphate fertilizer, are largely imported [4]. This import dependence further exposes the fertilizer industry to vulnerabilities in global supply chain disruptions.

Figure 1 presents NPK fertilizer production in Australia from 2000 to 2023, measured in metric tons. It focuses on the production volumes of three key inorganic fertilizers—Nitrogen, Phosphate, and Potash—in the Australian economy. Nitrogen production shows a slight decreasing trend from 2000 to 2004, followed by fluctuating trends for the remainder of the analysis. From 2015 onwards, Nitrogen production has remained steady, except for a dip in 2018. The trend of Nitrogen-based fertilizers shows an increasing pattern. The dominant Nitrogen-based fertilizers include urea and ammonia, which have been found to have significant long-term environmental impacts [10–12]. This is why the industry has decided to reduce Nitrogen fertilizer production in Australia. Phosphate production has remained relatively stable, with a few years of increased output. However, the trend line for Phosphate production has shown a downward trend due to recent instabilities. In contrast, Potash production exhibits a different pattern, showing a steady increase from 2000 to 2023. The trend line for Potash production is upward, as recent production has increased compared to past years.

Figure 2 illustrates NPK fertilizer consumption in the Australian economy from 2000 to 2023. Nitrogen fertilizer consumption in agricultural production is the highest, showing an upward trend except for recent years. Nitrogen-based fertilizers are primarily used in crops such as wheat, pulses, horticulture, canola, sugar, cotton, grains, and vineyards. The consumption of Nitrogen-based fertilizers has been increasing, except recent years. In contrast, Phosphate and Potash consumption have remained relatively steady over the last decade compared to the previous one. The trend for Phosphate consumption is declining. However, the trend line for Potash consumption is increasing. Potash consumption has sharply increased in the Australian agriculture sector over the last decade.

Figure 3 illustrates Australia’s export-to-import ratio of Nitrogen, Phosphate, and Potash from 2000 to 2023, along with the observed trend behavior. The export–import ratio of Nitrogen has shown a significantly decreasing trend from 2000 to 2020. However, from 2011 to 2021, the trend fluctuated, indicating an increase in imports of Nitrogen-based fertilizers compared to exports. For Phosphate, the ratio showed an increasing trend from 2000 to 2010, indicating a boost in exports over imports. The export–import ratio for Potash shows less impact, as the usage of Potash is lower compared to the other two dominant fertilizers. This ratio is close to zero, and the trend line is also static. Australia’s fertilizer industry relies heavily on imports, suggesting the need to explore untapped opportunities to strengthen and expand domestic production of fertilizers.

Fertilizers are inevitable in accelerating agro-production in Australia, but little is known about the factors affecting fertilizers consumption in Australia as well as relationship dimensions among the factors. Therefore, this paper aims to identify the market trends and factors that affect the consumption of fertilizers in the Australian economy due to its heavy reliance on imported fertilizers. The consumption pattern of Nitrogen and

Potash-based fertilizers is on the upward trend to prevail in the economy. The Phosphate consumption trend in agricultural activities has also increased in recent years. However, all three dominant fertilizers are heavily imported from overseas countries, which expose price rises and smooth supply chain management risks. Consequently, price increases spill over from producer to final consumer, threatening food inflation and overall economic stability [13–16]. In this research, we have pointed out a strong gap in the existing literature in the context of the Australian economy and other countries as well; that is, none of the past research shed light on trends in fertilizer consumption, including fertilizer export-to-import ratio and its trend. In addition, agro-economic factors such as; agri GDP, arable land, crop production, employment in the agricultural sector, agri export-to-import ratio, and agri research and development (Agri R&D) expenditure influence fertilizer consumption in the Australian economy. The key propositions in this research are the underlying factors that derive fertilizer consumption in the short-run and long-run dimensions. The moderating role of agricultural research and development expenditure with agricultural GDP is the extended value addition of this paper in the short- and long-run framework. The focus on agricultural research and development expenditure is an added innovation in the existing fertilizer consumption and agricultural GDP relationship model.

This research offers a novel perspective by examining how agricultural R&D expenditure, alongside agricultural GDP, influence fertilizer consumption, extending the existing theories on fertilizer consumption determinants. Unlike prior studies such as [14], whose findings primarily assessed influencing factors using country-specific time series or regional panel data and focused mainly on trend analysis, this study examines the agro-economic factors that rigorously drive fertilizer consumption in Australia. We propose a new conceptual framework in the literature and have identified gaps to analyze the short- and long-run impacts on fertilizer consumption. By incorporating agricultural R&D expenditure and the export-to-import ratio using quarterly data, this paper introduces new dimensions to studying fertilizer consumption in the Australian context.

The rest of this paper is arranged as follows: Section 1 describes a general introduction with the underlying objectives of this paper. The second section portrays the relevant literature to identify factors that lead to fertilizer consumption. The methodology section outlines the baseline models that support the paper's fundamental argument. The findings section presents the empirical results and interpretations derived from various econometric analyses. The final section concludes this paper by discussing the policy implications.

Factors Affecting Fertilizer Consumption: Conceptual Framework and Review

This study assesses influencing factors to determine fertilizer consumption, which will promote domestic agricultural activities and external markets for agricultural goods. The proposed factors were identified based on past studies that are aligned with the objectives of this study. Therefore, the key factors affecting fertilizer consumption are shown in Figure 4. This framework establishes the relationship among the factors influencing demand and determining fertilizer consumption in the Australian economy. We have identified six factors that influence fertilizer consumption in the Australian economy: arable land, agricultural GDP, crop production, agricultural export to import ratio, agricultural sector employment, and agri R&D expenditure.

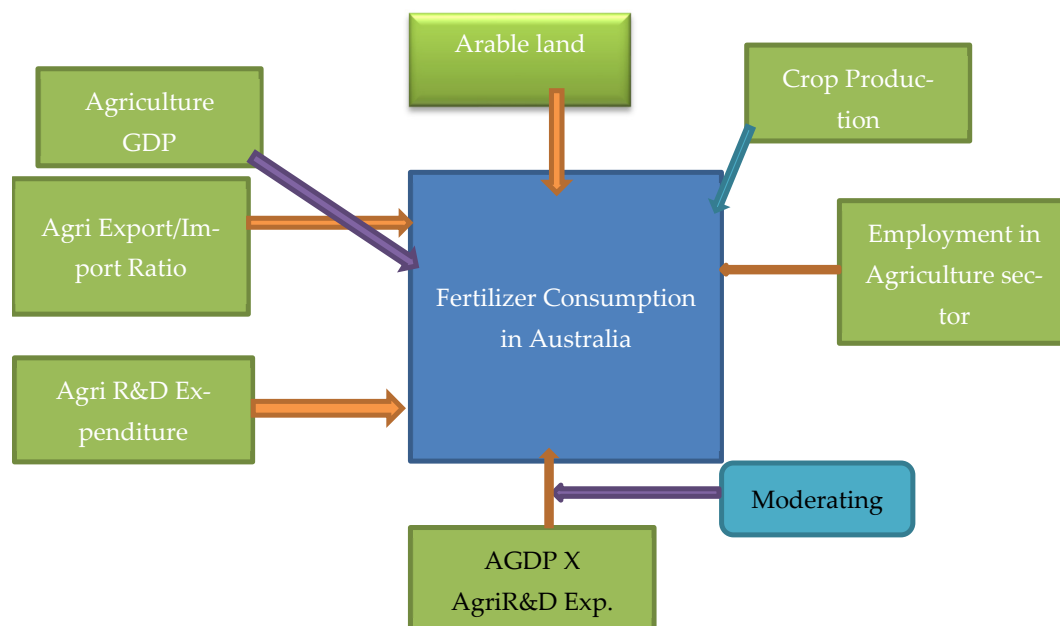


Figure 4. Conceptual framework of factors affecting fertilizer consumption (proposed by authors).

Moreover, the relationship dynamics between the interaction of agri GDP and agri R&D expenditure with fertilizer consumption is of interest. Figure 4 shows the individual impact of agri GDP and agri R&D expenditure on fertilizer consumption. However, we are expecting that the moderating effects of these two variables will produce a new avenue to think about this relationship chemistry. This framework justifies dominant factors affecting fertilizer consumption in the Australian agricultural sectors and its impact on the sustainable ago-economic development in Australia.

Fertilizer use in the Australian agro-economy has grown significantly, with Nitrogen fertilizer consumption increasing by 14% annually since the early 1990s [17,18]. This trend is driven by increasing arable land, increasing demand for commercial crops such as cereals and canola, and the matching demand of soil Nitrogen supply with crop demand [17]. However, refs. [19,20] found a decreasing trend of Nitrogen fertilizer application in the sugar industry since the mid-1990s, improving fertilizer use efficiency. Input subsidies, high-yielding varieties, and irrigated areas are directly affecting fertilizer consumption in many developing countries [12,21–23]. According to the findings of Refs. [24,25], nutrient application rates on agricultural land are increasing globally. Global Nitrogen (N) fertilizer from 1961 to 2018 has significantly increased from 3 to 26 kg N/ha [26]. Key factors in the Sub-Saharan African region include population growth, increasing food demand, and decreasing arable land [2,27]. Maximizing firms' profitability is also becoming a catalyst for increasing the amount of fertilizer consumption [2,17,24,28].

However, Australia's fertilizer production has declined recently, with a growing reliance on imports, particularly for Phosphorus and Potassium-based fertilizers from China, Morocco, Canada, and Russia [7]. Domestic production of Nitrogen-based fertilizers like urea remains significant and local production of Phosphorus and Potassium is minimal due to the limited availability of raw materials [29]. Ref. [30] observed a shifting trend towards high-yield fertilizers, which contain a higher concentration of essential nutrients for agricultural productivity. These fertilizers are more efficient, allowing farmers to apply fewer products while achieving the same or improved yield outcomes. Refs. [31,32] postulated that products such as urea and ammonium phosphate (DAP) have gained popularity due to their high nutrient contents, ease of application, and cost-effectiveness in crop productivity. Refs. [16,33–35] surveyed grain growers in Western Australia and

found that fertilizer decisions are most influenced by agronomic factors, such as rainfall, as well as logistical factors, including farm size, cropping areas, and the number of fertilizer applications per season.

Many previous studies have examined global trends expected to influence agriculture and fertilizer use over the next decade [11,36,37]. Previous studies are categorized into three types based on their contribution to this field. Firstly, the supply and demand dynamics and factors influence the supply and consumption of chemical fertilizers. For example, Refs. [9,38–40] postulate a wide range of responsible factors that were identified to determine supply and consumption of fertilizers varies across countries. In Pakistan's economy, fertilizer consumption has a positive and significant influence on Agri GDP. Government policy, infrastructure, and finance are the prerequisites for farmers to acquire fertilizers to boost demand for fertilizers in the Zimbabwean economy. In the Indian economy, irrigation, institutional credit, and subsidy are the factors that increase fertilizer consumption.

Secondly, the cropping system, farmers' characteristics, and technology adoption are factors regarding fertilizer usage. In the most recent studies, the socioeconomic characteristics of the household have been given attention as influencing factors [41,42]. Major socioeconomic factors influencing agriculture include the age and education level of the household head, farm size, and the degree of farmland fragmentation. Geographic factors include landform characteristics, drainage capacity, irrigation capacity, and topsoil thickness. Additionally, studies have examined several other characteristics, including those of the household head [39], family dynamics [43], farmland attributes [44], and technology features [45]. Promoting technology and farmers' perceptions of it reflect their understanding and access to such technologies [41]. Furthermore, the endowments of farmland resources—encompassing geological, physical, and chemical traits—significantly influence farmers' technology choices [46].

Thirdly, chemical fertilizers used in agricultural products have a negative impact on the environment. The overuse of chemical fertilizers has resulted in severe agricultural non-point source pollution in China [40,42,47,48]. Ref. [25] found that increased use of fertilizers harms the environment in the US economy. Ref. [49] argued that the issue is exacerbated by the increased use of urea fertilizer, which is both soluble and mobile in surface water flows. The growing demand for environmentally sustainable agricultural practices is influencing fertilizer production. Ref. [50] strongly suggested adopting organic and bio-fertilizers in Australia to reduce environmental impacts. Though these organic fertilizers are still a tiny part of the overall market, they are gaining momentum due to consumer demand for organic products and regulatory pressure to reduce nutrient runoff and greenhouse gas emissions. Fertilizer consumption in Australia is primarily driven by the requirements of large-scale cereal cropping, particularly in wheat, barley, and canola production. The report in Ref. [1] revealed that Nitrogen-based fertilizers, particularly urea, are the most widely used because they boost yields in Nitrogen-deficient soils.

Additionally, consumption patterns vary by region, with Western Australia, New South Wales, and Queensland being the highest consumers due to the large expanses of arable land dedicated to grain production [21,37,51]. Environmental concerns have become more significant in influencing fertilizer consumption patterns. The impact of fertilizers' use of nutrient overflow on water quality has led to tighter regulations in several Australian states [23,32]. As a result, policy adoption of imposing control while releasing fertilizers and precision agriculture technologies helps to minimize environmental impacts by reducing over-applications. Moreover, a vastly flexible climate also affects fertilizer consumption in the states of Australia [11]. The findings of Ref. [36] reveal that drought environments prevail in large parts of the country and can significantly reduce fertilizer use as farmers plant less or embrace conservative farming practices. According to Ref. [32],

fertilizer application rates drop considerably during extended dry periods, as farmers focus on maintaining soil health rather than increasing yields.

Moreover, commodity prices are a crucial determinant of fertilizer consumption in Australia, as they significantly influence farmers' profitability, leading to the use of inputs in farming [12]. Ref. [27] found that higher prices for agricultural products (e.g., wheat, barley, and canola) induce farmers to invest more in fertilizers to maximize yields. In contrast, when commodity prices drop, farmers reduce fertilizer inputs to cut costs, leading to fluctuations in fertilizer consumption. Ref. [17] documented that fertilizer use also shows regional variations. Western Australia shows the highest fertilizer usage per hectare, mainly due to its vast cropping areas and poor soil fertility. As a result, the adoption of precision agriculture technologies in these states has significantly improved the efficiency of fertilizer application. These technologies enable farmers to apply fertilizers more accurately, tailoring the application to the specific needs of the soil and crops. According to Ref. [30], the fertilizer market in Australia is extremely sensitive to global prices for raw materials. Phosphorus and Potassium, two dominant fertilizers, are imported mainly due to the absence of local reserves. Thus, global price volatility significantly affects local production costs and availability. The exchange rate of the Australian dollar with leading currencies also plays a crucial role in determining imported fertilizer prices in the home country, which in turn affects fertilizer usage and farmers' incentives for crop production [52]. Moreover, logistical challenges distort fertilizer consumption in Australia due to large distances between agricultural regions and fertilizer manufacturing or import hubs [53]. Farmers from remote areas must pay more to acquire fertilizers when transportation costs are higher from wholesalers to retailers.

Technological advancements, particularly, precision agriculture, policy restrictions, and climate diversities across the states, are transforming fertilizer use in Australia [45,54]. Ref. [6] shows that using precision farming tools such as GPS-guided machinery, soil mapping, and variable rate technology has led to more efficient fertilizer application in Australia. This technology reduces wastage and environmental impact while increasing crop yields. Hence, trending towards more sustainable farming practices is leading to an increase in the use of organic and bio-fertilizers. According to a report [21], organic farming is rapidly expanding with the use of organic fertilizers due to surging consumer demand. However, the market share of organic fertilizers is still tiny compared to total fertilizer consumption. Consumer awareness and policy applications for environmentally sustainable agricultural practices are imperative to boost the market share.

This study identifies a gap in the existing literature regarding a comprehensive examination of supply-side factors. Previous research has not explored the moderating role of specific factors in the relationship between key determinants of fertilizer consumption. This research focuses on two critical variables, agricultural R&D expenditure and the agricultural export-to-import ratio, and their impact on fertilizer consumption in Australia. Our study evaluates the independent effects of agricultural GDP and agricultural R&D expenditure on fertilizer consumption, but we also hypothesize that the interaction between agricultural GDP and R&D expenditure may exert a stronger influence on fertilizer consumption. To explore this, we employ an ARDL framework to investigate the relationship between agricultural GDP, R&D expenditure, and fertilizer consumption, with an emphasis on the moderating effects of agricultural GDP and R&D as a distinctive contribution of this study.

2. Methods and Data

2.1. The Models

The ARDL econometric model was used to analyze the relationships among various variables in Australia, including fertilizer consumption, agricultural GDP, the crop production index, arable land, agricultural employment, the ratio of agricultural exports to imports, and agricultural R&D expenditure. This analysis utilized quarterly data from the first quarter of 2000 to the fourth quarter of 2023. The detailed information on each variable, including their sources and units of measurement for this paper, is provided below.

Y: Fertilizer consumption (FConsm); kilograms per hectare of arable land.

X1: Agri GDP (Agri GDP); Agriculture; value added (% of GDP).

X2: Crop production index (Crop Prod); 2014–2016 = 100; aggregate volume of agricultural production for each year in comparison with the base period (2014–2016).

X3: Arable land (Arable land); % of land area.

X4: Employment in agriculture (Employment); % of total employment.

X5: Agri Exports/Imports ratio (Agri EXP/IMP Ratio); (Agricultural raw materials exports (% of merchandise exports)/Agricultural raw materials imports (% of merchandise imports)).

X6: Agri Research and Development Expenditure (Agri R&D Exp); Total value of agricultural R&D expenditure, real and nominal, 1992–2023, real prices (2023).

X7: $\text{Agri GDP} \times \text{Agri R\&D}$; Moderating variable, (Authors' calculation).

Data were collected from the World Bank Development Indicators (WDIs), the Food and Agriculture Organization (FAO), and the Australian Government Department of Agriculture, Fisheries, and Forestry, Industry-Based Information System (IBIS) World for this study. Finally, the authors' calculation mechanism was applied, and the data were converted from annual to quarterly using linear trend estimation. This study considers quarterly data covering the period from 2000Q1 to 2023Q4 for Australia. All variables are transformed into their natural logarithmic forms to de-trend the data and minimize seasonal effects.

In this research, we utilize the dynamic Autoregressive Distributed Lag (ARDL) bounds testing model to examine the long-run and short-run coefficients of the variables. To examine the short-run dynamic relationships among the variables, the Granger causality test is used. Unit root tests, including the [16,19,48,51]-Perron (Ng-P) tests, are used to assess the stationarity of the data. Additionally, a Vector Autoregressive Model (VAR) is employed to analyze the effects of a specific variable on itself and on all other explanatory variables, utilizing impulse response functions (IRFs). The Fully Modified Ordinary Least Squares (FMOLS) test is employed to assess the robustness of the findings in this study. This test will validate the empirical results concerning the factors influencing fertilizer consumption in Australia.

2.2. ARDL Bounds Testing Approach

This study investigates long-run relationship dynamics and error correction mechanisms among the variables of fertilizer consumption, agri value added, crop production, arable land, employment in agriculture, and agri export/import ratio, with agri R&D expenditure as one of the fundamental motives. The moderating effect of agricultural R&D expenditure and agricultural GDP on fertilizer consumption is examined using the bounds testing methodology. Equation (1) serves as the benchmark framework, without multiplicative interaction components, and is used as a reference before introducing frameworks that include these components. We present the traditional ARDL bounds methodology, as outlined by Ref. [55], in the format below. The ARDL version of the Error Correction Model (ECM) can be expressed as:

$$\Delta Y_{i,t} = Y_{1,i,t-k} + \sum_{i=1}^m \beta_1 \cdot \Delta X_{1,t-i} + \sum_{i=1}^m \beta_2 \cdot \Delta X_{2,t-i} + \sum_{i=1}^m \beta_3 \cdot \Delta X_{3,t-i} + \sum_{i=1}^m \beta_4 \cdot \Delta X_{4,t-i} + \sum_{i=1}^m \beta_5 \cdot \Delta Y_{t-i} + \sum_{k=1}^m \beta_6 \cdot \Delta X_{5,t-k} + \sum_{k=1}^m \beta_7 \cdot \Delta X_{6,t-k} + \sum_{k=1}^m \beta_8 \cdot \Delta X_{7,t-k} + \varepsilon_{i,t} \quad (1)$$

where Y = Fertilizer consumption, X_1 = Agri GDP, X_2 = Crop production, X_3 = Arable land, X_4 = Employment in agriculture, X_5 = Agri export/import ratio, X_6 = Agri R&D expenditure, X_7 = Moderating, t = time ($i = 1, 2, 3, \dots, n$), and ε = Error term.

2.3. Granger Causality Test

This paper examines the short-run relationships among the variables by conducting a Granger causality test. We believe this approach will enhance our understanding of the dynamics between the variables and clarify the directions of causality.

Ref. [10] developed a multivariate framework to examine the directional relationships among the variables. For example, in a multivariate framework, a time series x_{1t} causes another time series x_{2t} , when series x_{2t} works as a predicted catalyst with superior accuracy by using past values of x_{1t} and vice versa if other information is identical. The relationships among the variables are outlined in the following process.

$$\Delta Y_{i,t} = \theta_i + \sum_{k=1}^m \theta_{1,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta X_{5,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{i,t} \quad (2)$$

$$\Delta X_{1,i,t} = \theta_i + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{5,i,t-k} + \sum_{k=1}^m \theta_{7,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{1,i,t} \quad (3)$$

$$\Delta X_{2,i,t} = \theta_i + \sum_{k=1}^m \theta_{1,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{5,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{1,i,t} \quad (4)$$

$$\Delta X_{3,i,t} = \theta_i + \sum_{k=1}^m \theta_{1,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{5,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{1,i,t} \quad (5)$$

$$\Delta X_{4,i,t} = \theta_i + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{5,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{1,i,t} \quad (6)$$

$$\Delta X_{5,i,t} = \theta_i + \sum_{k=1}^m \theta_{1,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{6,i,t-k} + \varepsilon_{1,i,t} \quad (7)$$

$$\Delta X_{6,i,t} = \theta_i + \sum_{k=1}^m \theta_{1,i,k} \cdot \Delta X_{1,i,t-k} + \sum_{k=1}^m \theta_{2,i,k} \cdot \Delta X_{2,i,t-k} + \sum_{k=1}^m \theta_{3,i,k} \cdot \Delta X_{3,i,t-k} + \sum_{k=1}^m \theta_{4,i,k} \cdot \Delta X_{4,i,t-k} + \sum_{k=1}^m \theta_{5,i,k} \cdot \Delta Y_{1,i,t-k} + \sum_{k=1}^m \theta_{6,i,k} \cdot \Delta X_{5,i,t-k} + \varepsilon_{1,i,t} \quad (8)$$

2.4. Fully Modified Ordinary Least Squares (FMOLS) Test

Ref. [56] introduced a semi-parametric correction to the Ordinary Least Squares (OLS) estimator that effectively addresses the second-order bias caused by the endogeneity of the regressors within the model. This methodology produces optimal estimates for co-integrating regressions. The Fully Modified OLS (FMOLS) is applicable under the conditions that the regressors are either of full rank or co-integrated, particularly when they are integrated of order one, denoted as $I(1)$. Ref. [56] posits that FMOLS exhibits hyper-consistency for the coefficients of the deterministic regressors.

$$Y_n = \mu_1 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \varepsilon_n \quad (9)$$

3. Results and Analysis

Section 4 presents dynamic interpretations and practical implications of core propositions, using findings from various econometric analyses in this study. The Jarque–Bera test statistics support the acceptance and rejection of the null hypothesis of normal distribution

for each variable in Australia. The variables analyzed in this study generally adhered to a normal distribution, with the exceptions of fertilizer consumption, agricultural GDP, arable land, employment in agriculture, and agricultural R&D expenditure, as illustrated in Table 1.

Table 1. Descriptive statistics.

	FConsm	Agri GDP	Crop Prod	Arable Land	Employment	Agri EXP/IMP Ratio	Agri R&D Exp
Mean	5.533	2.569	4.544	3.656	4.774	3.963	7.627
Median	5.560	2.379	4.533	3.941	4.887	4.083	7.538
Maximum	5.949	3.945	4.984	4.160	6.050	5.651	7.908
Minimum	5.028	2.009	4.079	3.010	3.538	2.119	7.329
Std. Dev.	0.186	0.459	0.215	0.435	0.789	0.899	0.174
Skewness	−0.531	1.398	−0.245	−0.315	−0.178	−0.392	0.158
Kurtosis	4.030	4.511	3.141	1.332	1.662	2.533	1.516
Jarque–Bera	8.775	40.453	1.043	12.716	7.662	3.335	9.211
Probability	0.012	0.000	0.593	0.001	0.021	0.188	0.009
Sum	531.257	246.638	436.243	351.025	458.388	380.525	732.247
Sum Sq. Dev.	3.291	20.040	4.427	18.028	59.172	76.850	2.906
Observations	96	96	96	96	96	96	96

Additionally, the low standard deviation for all variables indicates that the data set exhibits a high degree of consistency and reliability. Furthermore, the variation between the maximum and minimum values was found to be within a reasonable range.

The results presented in Table 2 indicate that the unit root tests conducted in this study support the null hypothesis. Consequently, both acceptance and rejection of the null hypothesis are observed for the five independent and dependent variables at the I(0) level.

Table 2. Unit root tests results.

ADF		DF-GLS		Ng-Perron	
FConsm	Test statistic (Prob.)	FConsm	Test statistic (Prob.)	FConsm	Test statistic (Prob.)
Level:	−1.483 (0.53)	Level:	−1.337	Level:	−2.783 ***
1st Diff:	−10.102 (0.00) ***	1st Diff:	−10.150 ***	1st Diff:	−4.847 ***
Agri GDP		Agri GDP		Agri GDP	
Level:	−1.913 (0.32)	Level:	−1.288	Level:	−1.265
1st Diff:	−9.613 (0.00) ***	1st Diff:	−9.655 ***	1st Diff:	−4.845 ***
Crop Prod		Crop Prod		Crop Prod	
Level:	−2.499 (0.11)	Level:	−2.499 **	Level:	−2.555 **
1st Diff:	−6.649 (0.00) ***	1st Diff:	−6.591 ***	1st Diff:	−4.847 ***
Arable land		Arable land		Arable land	
Level:	−1.482 (0.56)	Level:	−0.581	Level:	−0.510
1st Diff:	−9.675 (0.00) ***	1st Diff:	−9.690 ***	1st Diff:	−4.837 ***
Employment		Employment		Employment	
Level:	−1.037 (0.73)	Level:	0.534	Level:	0.791
1st Diff:	−9.977 (0.00) ***	1st Diff:	−9.855 (0.00) ***	1st Diff:	−4.647 (0.00) ***
Agri Exp/Imp Ratio		Agri Exp/Imp Ratio		Agri Exp/Imp Ratio	
Level:	−1.619 (0.46)	Level:	−1.498	Level:	−1.501
1st Diff:	−9.604 (0.00) ***	1st Diff:	−9.650 ***	1st Diff:	−4.846 (0.00) ***
Agri R&D		Agri R&D		Agri R&D	
Level:	−0.379 (0.90)	Level:	0.105	Level:	0.168
1st Diff:	−9.768 (0.00) ***	1st Diff:	−9.742 ***	1st Diff:	−4.826 ***

Notes: * shows significance at the 10% level; ** shows significance at the 5% level; *** shows significance at the 1% level.

However, after performing first difference tests on both the independent and dependent variables, we reject the null hypothesis, which is supported by the unit root tests. This indicates that all variables of interest are stationary at the first difference, signifying first-order integration, denoted as $I(1)$.

The results of the diagnostic tests and Variance Inflation Factor (VIF) are presented in Table 3. The F-statistics and probability values indicate no evidence of serial correlation or autocorrelation in this study. The Breusch–Pagan–Godfrey test confirms that the residuals do not exhibit a heteroskedasticity trend. The Jarque–Bera statistic value of 1.326 (p -value 0.2469) suggests that the data are normally distributed. The VIF test was employed to assess multicollinearity among the variables, and the results confirm that no multicollinearity exists among the variables. Therefore, the findings of this study can be considered valid and reliable, supporting policy-level implications.

Table 3. Results of diagnostic tests and variance inflation factor.

Tests	F-Statistic (Prob)	Variables	VIF
Serial Correlation	2.366 (0.12)	Agri GDP	4.6184
Heteroskedasticity	1.866 (0.06)	Crop Prod	4.3790
Autocorrelation	1.285 (0.256)	Arable Land	3.4764
Normality Test 1.326 (0.246)		Employment	3.1013
		Agri Exp/Imp Ratio	2.8170
		Agri_R&D Exp	1.0303

Table 4 presents the findings on the long-term relationships among the independent, moderating, and dependent variables in this study. This paper adopts a distinctive approach by utilizing quarterly data from the first quarter of 2000 to the fourth quarter of 2023. Being one of the dominant OECD economies, Australia still depends on imported fertilizer for its internal demand. The fundamental propositions of this paper are to identify the trend in fertilizer production and consumption in Australia and the leading factors. The results of the ARDL bound test reveal a long-term co-integrating relationship between factors affecting fertilizer consumption. Crop production has a significant long-run co-integrating relationship with fertilizer consumption at a level of 1 percent. The agriculture export-to-import ratio and agriculture R&D expenditure also show a 5 percent level co-integration relationship with fertilizer consumption in the long run. These findings provide guidelines for the policymakers to a great extent for boosting the Australian fertilizer industry. Furthermore, the moderating effects of agri GDP and agri R&D expenditure are also significant at a 1 percent level in the long run. Interestingly, the moderating relationship has a more substantial impact on fertilizer consumption in the long run than the individual impact of each.

The error correction equation is presented in the following:

$$\begin{aligned}
 EC = FConsm_p - & (-0.5997 \times \text{Agri GDP} + 0.1024 \times \text{Crop Prod} + 0.1524 \times \text{Arable Land} + \\
 & 0.1533 \times \text{Employment} + 0.0068 \times \text{Agri EXP/IMP_RATIO} + 0.7653 \times \text{Agri R\&D Exp} + \\
 & 0.0788 \times \text{AGDP} \times \text{Agri R\&D Exp} - 2.0912)
 \end{aligned}
 \quad (10)$$

Table 5 outlines the short-run error correction mechanism related to fertilizer consumption and other explanatory variables in this study. The results indicate that the majority of the explanatory variables, except for arable land and agri GDP, quickly return to equilibrium through this mechanism. Specifically, crop production, the ratio of agricultural exports to imports, and agricultural R&D expenditure adjust back to equilibrium in the short term when discrepancies arise in their relationship with fertilizer consumption.

Additionally, the moderating effects of agricultural GDP and the export-to-import ratio were found to be significant in the short-run error correction process concerning fertilizer consumption. These findings suggest that all variables, including the moderating factors, play an important role in influencing fertilizer consumption in Australia. Notably, the adjustment and correction occur rapidly, typically within a year.

Table 4. Results of ARDL Bounds Test.

Variable	Coefficient	Std. Error	<i>t</i> -Statistic	Prob.
Fconsp (−1)	0.823114	0.102535	8.027671	0.0000
Agri GDP	13.24909	65.93153	0.200952	0.8412
Crop Prod	0.458682	0.172531	2.658549	0.0095
Arable Land	4.920441	19.77319	0.248835	0.8041
Employment	0.051960	0.045617	1.139049	0.2582
Agri Exp/Imp Ratio (−1)	0.062044	0.038921	1.994101	0.0450
Agri_R&D Exp (−1)	0.503404	1.281090	2.266354	0.0262
Agri GDP × Agri R&D (−1)	0.854093	0.504750	2.992112	0.0046
C	−0.708611	6.205425	−0.114192	0.9094
F-Bounds Test	Null Hypothesis: No levels relationship			
Test Statistic	Value	Signif.	I(0)	I(1)
Asymptotic: n = 1000				
F-statistic	2.936426	10%	1.92	2.89
k	7	5%	2.17	3.21
		2.5%	2.43	3.51
		1%	2.73	3.9
Finite Sample: n = 80				
Actual Sample Size	94	10%	2.017	3.052
		5%	2.336	3.458
		1%	3.021	4.35

Table 5. Error correction representation for the selected ARDL model.

ECM Regression				
Restricted Constant and No Trend				
Variable	Coefficient	Std. Error	<i>t</i> -Statistic	Prob.
D (Crop Prod)	0.458682	0.143540	3.195495	0.0020
D (Agri Exp/Imp Ratio)	−0.062044	0.034044	−2.822431	0.0112
D (Agri_R&D_Exp)	0.903404	1.125756	2.579070	0.0118
D (AGDP × Agri R&D)	−0.854093	0.446881	−1.911231	0.0506
CointEq (−1) *	−0.338859	0.077303	−4.383526	0.0000

* *p*-value incompatible with *t*-Bounds distribution.

Figure 5 displays the results of the stability diagnostic test of the ARDL model for the data. The CUSUM test results confirm that the model is significant at the 5 percent level and remains stable, as the data points fall within the upper and lower bounds. Additionally, Figure 5 presents the results of the CUSUM Square test, which further supports the goodness of fit of the ARDL model. Furthermore, this study includes the F-bound test, which yields significant results at both the 5 percent and 1 percent levels, indicating a strong fit for the model.

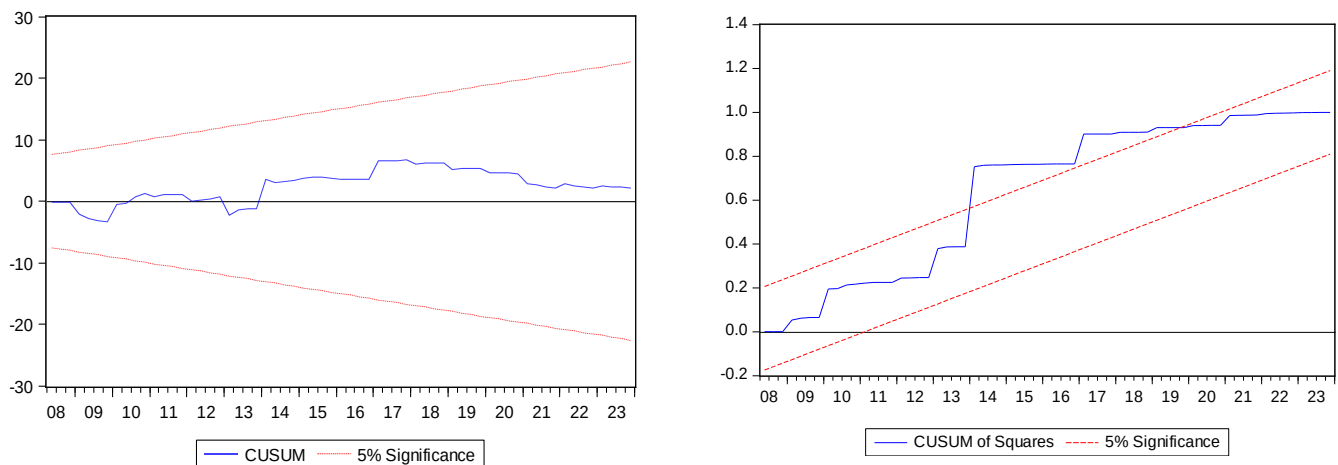


Figure 5. CUSUM and CUSUM Squares tests.

The Granger causality test was employed to explore the short-run causal relationship dynamics among the dependent and independent variables.

The results of the Granger causality test are presented in Table 6. Both bidirectional and unidirectional causal links among the variables of fertilizer consumption, agri GDP, crop production, arable land, employment, agri-to-import ratio, and R&D expenditure are found in this study.

Bidirectional causality has been found between agriculture GDP and fertilizer consumption in Australia. It directs agricultural GDP, which is crucial to promote fertilizer consumption and vice versa in the short-run. Similarly, bidirectional causal links have been documented between arable land and fertilizer consumption, when the economy has more land for agricultural activities, fertilizer consumption will automatically increase and vice versa in the short run. Crop production also plays a bidirectional role with fertilizer consumption. Additionally, bidirectional causality has been found between employment in agriculture and fertilizer consumption, as well as the agri export–import ratio and fertilizer consumption in this study. These findings are logically plausible in the context of the Australian economy, aiming to promote sustainable fertilizer consumption and production in the short run.

This study also acknowledged unidirectional causality between agriculture R&D expenditure and fertilizer consumption, showing that agriculture research and development significantly impact fertilizer consumption from various dimensions. Therefore, investing more in agriculture research and development investment is a time demand and imperative for the Australian economy. Agri GDP, crop production, agriculture value added to arable land, agri export-to-import ratio, and agri GDP show the unidirectional causal relationship in the short run in the framework demand–production nexus of fertilizer in the Australian economy. Furthermore, unidirectional causal links were found between arable land and crop production in the Australian economy based on quarterly data from 2000 to 2023.

Findings from the Granger causality test indicate a strong bidirectional causal relationship among the instrumental variables (IVs), including crop production, arable land, employment in the agricultural sector, and the agricultural export-to-import ratio. Therefore, we suspect the presence of an endogeneity issue among the explanatory variables in this study, which could mislead the results and lead researchers to draw biased policy interpretations. To address this bias, an IV-based endogeneity test was conducted, and the results are presented in Table 7. The results confirm that no endogenous relationship exists among the instrumental variables in this study. Hence, the short-run findings of the Granger causality test are accurate for drawing policy recommendations in the short run.

Table 6. Results of pairwise Granger causality test.

Null Hypothesis:	Obs	F-Statistic	Prob.
Agri GDP does not Granger Cause FCONSMP FCONSMP does not Granger Cause Agri GDP	95	5.863 8.009	0.005 0.000
Crop Prod does not Granger Cause FCONSMP FCONSMP does not Granger Cause Crop Prod	95	5.049 3.061	0.005 0.035
Arable Land does not Granger Cause FCONSMP FCONSMP does not Granger Cause Arable Land	95	7.892 6.878	0.006 0.008
Employment does not Granger Cause FConsmP FConsmP does not Granger Cause Employment	95	4.097 3.174	0.045 0.078
Agri EXP/IMP_Ratio does not Granger Cause FCONSMP FCONSMP does not Granger Cause EXP/IMP Ratio	95	9.105 6.006	0.000 0.004
Agri R&D _EXP does not Granger Cause FCONSMP FCONSMP does not Granger Cause Agri R&D_EXP	95	5.444 0.647	0.021 0.423
CROPPROD does not Granger Cause Agri GDP Agri GDP does not Granger Cause CROPPROD	95	0.589 4.3720	0.444 0.039
Arable Land does not Granger Cause Agri GDP Agri GDP does not Granger Cause Arable Land	95	0.529 4.367	0.468 0.039
Employment does not Granger Cause Agri GDP Agri GDP does not Granger Cause Employment	95	1.200 0.276	0.276 0.600
Agri EXP/IMP Ratio does not Granger Cause Agri GDP Agri GDP does not Granger Cause Agri EXP/IMP Ratio	95	7.295 0.264	0.008 0.608
Agri R&D EXP_does not Granger Cause Agri GDP Agri GDP does not Granger Cause Agri R&D EXP	95	0.078 1.915	0.780 0.169
Arable Land does not Granger Cause Crop Prod CROPPROD does not Granger Cause ARABLE LAND	95	4.701 0.996	0.032 0.320
Employment does not Granger Cause Crop Prod Crop Prod does not Granger Cause Employment	95	2.597 0.016	0.110 0.899
EXP/IMP Ratio does not Granger Cause Crop Prod Crop Prod does not Granger Cause EXP/IMP Ratio	95	2.026 0.144	0.158 0.704
Agri R&D EXP does not Granger Cause Crop Prod Cropp Rod does not Granger Cause Agri R&D EXP	95	1.812 4.273	0.181 0.041
Employment does not Granger Cause Arable Land Arable Land does not Granger Cause Employment	95	0.361 1.279	0.548 0.260
EXP/IMP Ratio does not Granger Cause Arable Land Arable Land does not Granger Cause agri EXP/IMP Ratio	95	0.918 0.540	0.340 0.464
Agri R&D EXP does not Granger Cause Arable Land Arable Land does not Granger Cause Agri R&D EXP	95	0.030 12.090	0.862 0.000
EXP/IMP Ratio does not Granger Cause EMPLOYMENT EMPLOYMENT does not Granger Cause EXP/IMP Ratio	95	0.000 4.063	0.984 0.046
Agri R&D EXP does not Granger Cause EMPLOYMENT Employment does not Granger Cause Agri R&D EXP	95	0.779 2.791	0.379 0.098
Agri R&D EXP does not Granger Cause EXP/IMP_Ratio Agri EXP/IMP Ratio does not Granger Cause Agri R&D EXP	95	2.790 0.103	0.098 0.748

In this research, we suspect that there may be a structural breakpoint due to the COVID-19 regime, which could affect the accuracy of the data and, consequently, the validity of the overall findings. The results of the Chow structural breakpoint test are shown in Table 7. The results confirm that there is no structural breakpoint identified from 2000 to 2023. Since we analyzed quarterly data, this acted as a catalyst to eliminate structural breaks. To ensure reliable findings, we conducted a structural breakpoint test.

Table 7. Results of endogeneity and Chow breakpoint tests.

	Value	df	Probability
Difference in J-stats	3.25479	0	0.1479
J-statistic summary:			
	Value		
Restricted J-statistic	3.8347		
Unrestricted J-statistic	8.2547		
Chow Breakpoint Test (2020Q1 to 2022Q4)			
F-statistic	3.1326	Prob. F(3,86)	0.1196
Log likelihood ratio	9.9568	Prob. Chi-Square(3)	0.0189
Wald Statistic	9.3982	Prob. Chi-Square(3)	0.02420

The robustness check of the findings is a crucial aspect of this study, ensuring the validity of the research from another dimension. Accordingly, we have applied fully modified least squares (FMOLS) to check the consistency of findings from various econometric models. FMOLS is the best predictor to minimize endogeneity and simultaneity bias among the regressors of the study, and it offers a co-integrating relationship among the endogenous and exogenous variables.

This research has substantial value addition through innovation in the underlying propositions that identify factors affecting fertilizer consumption and its moderating effects in the context of the Australian economy. The findings of the FMOLS test reported in Table 8 confirm that most of the explanatory variables have a long-run co-integration effect on fertilizer consumption in Australia. However, employment has been found to have an insignificant impact on fertilizer consumption in Australian agronomy. The moderating relationships of agri GDP with agri R&D expenditure were also found at one-percent-level significance in the nexus of fertilizer consumption. Thus, the findings of FMOLS are aligned with the findings of the ARDL bound test among the variables in the long run.

Table 8. Fully modified least squares (FMOLS).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
AGRI GDP	0.121375	0.082126	1.477916	0.1588
CROPPROD	0.278789	0.299536	3.930737	0.0046
ARABLELAND	0.094632	0.198951	2.475658	0.0355
EMPLOYMENT	0.082830	0.119049	0.695764	0.4884
AGRI EXP/IMP_RATIO	0.020417	0.047544	3.429439	0.0087
AGRI_R&D_EXP	0.334066	2.014732	5.654843	0.0006
AGDP $\times$ Agri R&D EXP	0.777519	0.839963	4.282817	0.0030
C	21.65646	15.70321	1.379110	0.1714
R-squared	0.513165	Mean dependent var		5.534699
Adjusted R-squared	0.473994	S.D. dependent var		0.186958
S.E. of regression	0.135594	Sum squared resid		1.599551
Long-run variance	0.069121			

Figure 6 explains the Monte Carlo accumulated response to a one standard deviation innovation shock on all explanatory variables and its impact on fertilizer consumption over the period. When the shock is applied to agri GDP, it positively affects fertilizer consumption, but spikes flatter. Similarly, positive impacts are observed in the case of crop production, arable land, and export-to-import ratio on fertilizer consumption. This positive shock implies that the shock on these variables will affect fertilizer consumption negatively in the Australian economy. However, the Monte Carlo accumulated response of

employment found a negative impact on fertilizer consumption over time. Moreover, the moderating effect is positive if shock applies in one standard deviation innovation.

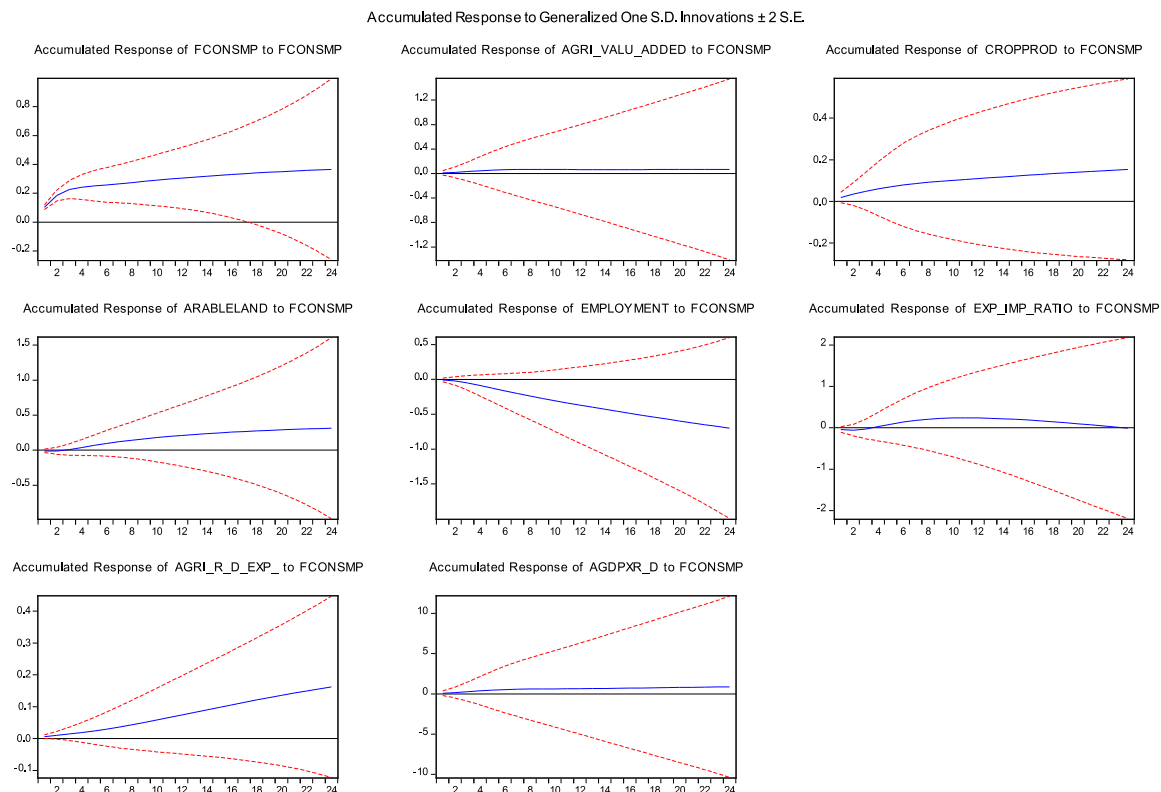


Figure 6. Monte Carlo impulse response function. Red lines are upper and lower bounds, and blue line is the actual response.

4. Conclusions and Policy Implications

This study examined the trend and underlying factors accountable for fertilizer consumption in the Australian agricultural sector from 2000 to 2023. To portray the existing scenarios, the trend analysis investigated three dimensions: fertilizer consumption, production, and export/import ratio. The production of Nitrogen-based fertilizers had a fluctuating trend from 2000 to 2015. However, it is in stable shape nowadays, as documented in this study. Nitrogen-based fertilizer consumption is highest for the period of 2000 to 2023 in comparison with Phosphate and Potash. This is a sign of the dominance of Nitrogen-based fertilizers in Australian agricultural production. However, production is less than consumption; thus, predominantly depending on imported fertilizers is a severe risk to agriculture production.

The other two elements of NPK, namely, Phosphate and Potash, are still predominantly dependent on imports from countries like China, Morocco, Russia, and Canada, which intensely distorted the price and usage in the local market. Phosphate production has oscillated from 2000 to 2019; onwards, production looks stable, though the trend line spiked down. The consumption trend of Phosphate and Potash is increasing steadily, though the rate of Potash consumption is slow. Moreover, the export-to-import ratios of NPK fertilizers are recorded as frustrating in the Australian economy. The ratio values for the last 24 years confirmed that imports dominate Australian fertilizer consumption as the ratio values fall below one for NPK. In the era of globalization, balancing a country's trade balance is a vital aspect of enhancing sustainable economic growth. The Australian fertilizer market deviates from this philosophy, relying heavily on imported fertilizers. This trend hampered

overall agricultural activities in the Australian economy due to fertilizer price increases and farm profit for sustainable agricultural practices.

Moreover, this study also found that a significant long-run relationship exists among the variables of crop production, agri export–import ratio, agri R&D expenditure, and the moderating effects of agri GDP and agri R&D expenditure on fertilizer consumption. However, agriculture employment has no long-run relationship with fertilizer consumption. In the short run, the error correction mechanism shows that all of the variables quickly return to equilibrium except the independent variable arable land.

The Granger causality test results show that bidirectional causality exists among the variables of agri GDP to fertilizer consumption, arable land to fertilizer consumption, employment to fertilizer consumption, and export–import ratio to fertilizer consumption. Moreover, unidirectional causality exists among the variables of crop production to fertilizer consumption, agri R&D expenditure to fertilizer consumption, agri GDP to crop production, agri GDP to arable land, agri export–import ratio to agri GDP, arable land to crop production, employment to agri export–import ratio, and crop production to agri R&D expenditure. Robustness checks further confirm that most of the variables have a fully modified co-integrating relationship with fertilizer consumption, except the employment and agriGDP variables in Australia. The impulse response function shows an accumulated response of one standard deviation innovation. All of the variables positively react to fertilizer consumption if shock applies to fertilizer consumption, except employment. The accumulated response function of employment is negative with fertilizer consumption.

Policymakers are advised to prioritize increased investment in agricultural research and development (R&D) to promote sustainable fertilizer consumption in the Australian agricultural sector. They should focus on enhancing funding for research in precision farming, soil health management, and alternative fertilizers. Such policies can reduce dependency on imported fertilizers and stabilize domestic consumption. Additionally, boosting domestic fertilizer production will help mitigate price uncertainty and support local agricultural production, thereby increasing the share of agricultural GDP as a percentage of total GDP. To ensure long-term sustainability, policymakers must balance productivity needs with environmental concerns by fostering innovation, implementing regulations, and supporting farmer initiatives.

5. Limitations of This Study

This study provides significant insights into the trends and factors influencing fertilizer consumption in Australia, as well as the moderating effect of agricultural research and development (R&D) investment. However, several limitations must be acknowledged. Although this study investigates relationships between variables, it may not fully establish causality. External factors such as government policies, global market trends, and climatic conditions could potentially confound the results. Moreover, the findings are specific to Australia and may not be directly applicable to other agricultural economies with differing soil conditions, climates, or policy frameworks.

Other influences on fertilizer consumption, including farmer perceptions, technological adoption, and changes in soil fertility are not comprehensively captured in the analysis, which could result in omitted variable bias. Furthermore, external shocks such as economic downturns, trade restrictions, or sudden policy changes (e.g., subsidies, carbon taxes) may impact fertilizer consumption in ways not accounted for in the model.

Despite these limitations, this research offers meaningful insights into fertilizer consumption trends and the role of R&D investment. Future studies could address these gaps by incorporating more rigorous data, employing advanced econometric techniques, and considering a broader array of environmental and economic factors.

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