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Analyzing Saudi Potato Demand: A Comparative Evaluation of AIDS, QUAIDS, and Rotterdam Models

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ABSTRACT

This study evaluates and compares the empirical performance of three demand system models—Almost Ideal Demand System (AIDS), Quadratic AIDS (QUAIDS), and Rotterdam—in estimating price, income, and cross-price elasticities for potato demand in Saudi Arabia. Given the volatile nature of emerging-market data, the study aims to identify the most suitable model for accurately capturing consumer behavior in the Saudi potato market. The empirical analysis highlights the strengths and limitations of each model in handling price and income fluctuations. While the AIDS and QUAIDS models proved theoretically attractive, both exhibited estimation challenges in this context, including statistically insignificant coefficients, violations of homogeneity and symmetry, and unstable elasticity results. QUAIDS, though capable of capturing nonlinearities, suffered from convergence issues and multicollinearity under volatile conditions. These limitations prompted the adoption of the Rotterdam model, which provided a more stable and theoretically consistent forecast. The study also implements homogeneity and symmetry restrictions within Rotterdam's framework (RMLE) to enhance model reliability. Diagnostic tests, including Wald tests for coefficient significance and Durbin-Watson tests for residual autocorrelation, confirm the robustness of the findings.

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In addition, the analysis highlights the practical significance of elasticity estimation for policy design and food security planning. The results offer valuable insights for policymakers and market analysts to understand demand elasticity and improve forecasting in Saudi Arabia's potato sector.

Keywords: Price Elasticity; Potatoes; AIDS; QUAIDS; Rotterdam

1. Introduction

The agricultural sector in Saudi Arabia faces formidable challenges, including water scarcity, high production costs, and heavy reliance on food imports. Despite these hurdles, potato cultivation has witnessed significant growth in recent years, bolstered by government initiatives to promote sustainable agriculture and reduce import dependency. Potatoes rank among the kingdom's strategic crops, playing a pivotal role in meeting nutritional needs and advancing food security, particularly given their rising domestic consumption and versatility in both fresh and processed forms, such as fries and chips. Despite climatic constraints, Saudi Arabia has enhanced its agricultural production through modern irrigation techniques and advanced agricultural solutions, including protected farming systems. This progress is evident in the surge of output from 422 metric tons in the 1970s to 605,000 tons in 2022, a 4.7% annual increase, propelling the kingdom to 54th place globally in potato production [1].

The first decade of the 21st century marked a transformative period in agricultural policy, with substantial government investments in infrastructure and subsidized loans for farmers. These measures expanded cultivated areas and boosted productivity. However, global climate shifts and COVID-19 disruptions strained supply chains, prompting the kingdom to reinforce farmer support and adopt innovative water management strategies, sustaining production growth despite external shocks. Despite these advancements, Saudi Arabia relies heavily on imports to meet peak domestic demand, particularly during off-season periods. In 2022, the value of potato imports (fresh or chilled) reached $55 million, a 49% increase from 2021. Key suppliers, including the Netherlands, Germany, the United States, and India, account for nearly 79% of total imports. This dependence highlights the interplay between rising local demand, driven by urbanization, the expansion of the fast-food industry, shifting dietary preferences toward Western-style consumption, and the need to strengthen domestic supply chains [1].

However, a clear empirical understanding of consumer behavior in this context remains underdeveloped, limiting the ability to formulate evidence-based policy interventions. Projections indicate sustained demand growth for potatoes, driven by population increases and shifting consumer preferences. This trend highlights the importance of examining domestic demand dynamics, including responsiveness to price and income fluctuations, to inform policies that enhance local production, diversify import sources, and optimize food security strategies. Leveraging econometric models, such as the Rotterdam framework, which has been validated for volatile markets, this study provides quantitative insights into consumer behavior and demand elasticities. Accordingly, the study aims to provide a clearer understanding of how Saudi consumers respond to changes in price, income, and cross-price elasticity in the potato market.

The Saudi potato sector reflects a complex interplay of growth, vulnerability, and strategic potential, shaped by decades of agricultural evolution and shifting global dynamics. Between 1990 and 2022, production surged by over 1,300%, reaching a peak of 578,108 tons in 2021, driven by expanded cultivation areas and technological advancements in irrigation and farming practices. Government policies aimed at bolstering food security have played a pivotal role, aligning with rising domestic demand driven by population growth, urbanization, and evolving dietary preferences. Exports reached their zenith in 2010, with 135,488 tons valued at $26.8 million, signaling robust international competitiveness, particularly in regional markets [1].

However, post-2010 volatility marked by fluctuating export volumes exposed vulnerabilities linked to do-

mestic market saturation and global supply chain disruptions. This highlights the importance of infrastructure investments in cold storage and quality standardization to enhance the stability of export performance. Despite these production gains, imports remain critical to bridging supply gaps, peaking at 127,074 tons in 1990 and maintaining an upward trajectory in value, reaching $55 million by 2022 [1]. This reliance stems from seasonal yield variability, climate-driven challenges, and surging demand from fast-food and processing industries, with nearly 79% of imports sourced from the Netherlands, India, and the U.S. [1]. Rising global prices and logistical bottlenecks further strain domestic pricing strategies, underscoring the need to scale local efficiency and storage capacity. The sector's socio-economic significance is evident in its contributions to rural employment and agricultural GDP; yet, its resilience is tested by water scarcity, climate change, and geopolitical trade risks.

Addressing these challenges requires a multifaceted approach: prioritizing precision agriculture and drought-resistant crop varieties to enhance yield stability, modernizing supply chains through investment in storage and processing infrastructure, diversifying export markets via strategic trade agreements, and expanding farmer support through subsidies and training in sustainable practices. By balancing these measures, Saudi Arabia can transform its potato sector into a resilient pillar of food security, reducing its dependency on imports while capitalizing on global export opportunities. This dual focus on innovation and strategic planning will mitigate volatility and position the kingdom to navigate evolving market demands and environmental pressures, ensuring long-term agricultural sustainability and economic stability. Therefore, the primary objectives of this study were to fill the empirical gap in consumer demand systems by evaluating and comparing the performance of three prominent demand models, namely, the Almost Ideal Demand System (AIDS), Quadratic AIDS (QUAIDS), and Rotterdam models, in estimating price, income, and cross-price elasticities for potato demand in Saudi Arabia. The research framework guiding this analysis is illustrated in **Figure 1**, which outlines the integration of theoretical assumptions and demand models to generate elasticity estimates and support policy recommendations. This framework supports policy design by identifying the most appropriate model for capturing demand behavior under market volatility.

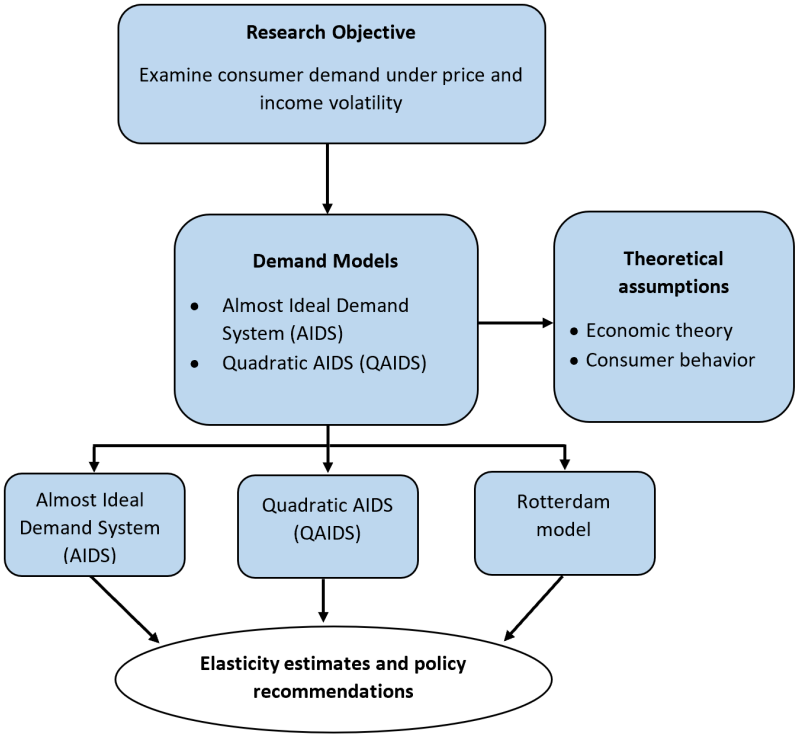

Figure 1. Research framework for examining consumer demand for potatoes.

1.1. Previous Studies

1.1.1. Global Empirical and Theoretical Contributions

The analysis of agricultural demand, particularly for staple crops like potatoes, has been extensively explored through various econometric models, revealing nuanced insights into consumer behavior, price sensitivity, and income effects across diverse contexts. The foundational Almost Ideal Demand System (AIDS), introduced by Deaton and Muellbauer[2], has been pivotal in enabling the simultaneous examination of multiple goods, incorporating price and income dynamics. Recent theoretical contributions have enhanced the representation of consumer behavior by revisiting foundational concepts, such as Engel curves. One such contribution is a retrospective analysis of Engel's Law, which highlights the evolution of demand modeling and the necessity of accounting for expenditure hierarchies and income heterogeneity in modern systems[3]. Similarly, the Exact Affine Stone Index (EASI) demand system was introduced as a flexible alternative to AIDS and QUAIDS, addressing core limitations in their functional forms and improving empirical fit[4].

Methodological innovations have further refined the analysis of demand. Barnett and Seck[5] compared the Rotterdam and AIDS models, highlighting the latter's robustness in recovering actual elasticities through Monte Carlo simulations. Tiffin and Arnoult[6] introduced Bayesian methods to account for socio-economic factors influencing dietary choices in the United Kingdom (UK). These advancements complement regional studies, such as those by Rono et al.[7] in Kenya, where potatoes emerged as elastic substitutes for other tubers, classified alongside cassava as necessities.

These models have been applied in numerous empirical studies worldwide. For example, Bahloul and Ahmed[8] demonstrates the utility of AIDS in assessing Egyptian potato exports, where price elasticity varied significantly across markets; Russia, Greece, and Italy exhibited demand reductions of 1.049%, 1.009%, and 0.347%, respectively, per 1% price increase. Such findings underscore the critical role of price sensitivity in international trade, a theme echoed by Huber[9], a U.S.-focused study, which identified greater consumer responsiveness to specialty potato prices compared to traditional varieties like Russet, suggesting niche market opportunities.

Consumer preferences and socio-economic dynamics further complicate demand patterns. Richards et al.[10] attributed declining U.S. potato consumption to shifting tastes rather than mere price or income changes, a trend mirrored in Hsieh et al.[11] analysis of organic potato demand, where rising prices reflected growing consumer trust in traceability systems, as seen in Italy.

1.1.2. Regional and Middle Eastern Contexts (Including Kenya, Egypt, and Saudi Arabia)

Demand system models have also been applied in regional contexts. In Kenya, Rono et al.[7] found that potatoes emerged as elastic substitutes for other tubers, classified alongside cassava as necessities. Another applied the QUAIDS model to Kenyan households and found that income effects varied significantly across food groups[12]. Similarly, Ilboudo[13] used household-level data to assess food demand elasticities in Kenya, noting that even staple foods (like potatoes) may shift between normal and inferior goods depending on income strata and regional supply stability. Nuani et al.[14] also reinforced the variability of demand elasticity, finding that Kenyan households perceive sweet potatoes and yams as inferior goods, in contrast to the necessity status of Irish potatoes.

In Bangladesh, Huq et al.[15] and Ahmed and Shams[16] highlighted potatoes as necessities with inelastic demand, though higher-income households prioritized protein-rich foods, illustrating income's stratified impact.

In the Saudi context, Alnafissa and Alderiny[17] applied the Almost Ideal Demand System (AIDS) to analyze the demand for imported honey, demonstrating the model's capability to capture price and income sensitivities in the Saudi food market. Their findings confirmed the applicability of demand system models to import-dependent commodities and provided a methodological precedent for the present study's application to potatoes. Despite this global insight into wealth, Saudi

Arabia's potato demand remains underexplored. While Okasha [18] noted the expansion of cultivation driven by agricultural investments, and Ghanem et al. [19] proposed water-efficient production strategies, gaps persist in understanding market dynamics, particularly in terms of price elasticity and substitution effects within a volatile, import-dependent context. The current study addresses this gap by employing the Rotterdam model, which has been validated for unstable markets, to analyze Saudi import data, providing actionable insights for trade diversification and food security. This research bridges a critical void by synthesizing global methodological advancements and regional findings, informing policies tailored to Saudi Arabia's unique economic and consumer landscape.

2. Methods

2.1. Methodology

The analysis of consumer demand systems, such as the Almost Ideal Demand System (AIDS), Quadratic Almost Ideal Demand System (QUAIDS), and the Rotterdam model, plays a pivotal role in understanding economic behavior, particularly in estimating income and price elasticities for policy design and market forecasting. These models, although foundational, exhibit distinct strengths and limitations that depend on contextual factors such as data structure, economic conditions, and analytical objectives. Comparative studies underscore the nuanced trade-offs between model complexity and empirical performance. For instance, Meyer et al. [20] evaluated six demand systems via Monte Carlo simulations, revealing that AIDS excels in own-price elasticity estimation for 6-commodity frameworks, while QUAIDS and higher-rank models, such as AIDS, do not universally outperform more straightforward specifications, challenging the assumption that complexity guarantees accuracy. Similarly, after applying Belgian time-series data, Decoster and Vermeulen [21] found AIDS and QUAIDS robust for indirect tax simulations, with AIDS demonstrating superior stability across goods.

In contrast, the Rotterdam model lagged in predictive precision despite its computational flexibility. Barnett and Seck [5] further dissected these dynamics, showing that nonlinear AIDS outperforms Rotterdam under high substitution elasticity regimes, though Rotterdam proves advantageous for weakly separable aggregations. Their work cautions against linear approximations of AIDS, which distort elasticity estimates. Complementing these insights, Cranfield [22] highlights how development levels influence model suitability, AIDS aligns with low-income economies, while QUAIDS better captures nuanced preferences in middle- and high-income contexts. Furthermore, the reliability of results heavily depends on the quality and consistency of the underlying data. To enhance validity, this study utilized official Saudi import and consumption records, which were subjected to data cleaning, interpolation, and outlier checks to address missing values and inconsistencies between sources. Although out-of-sample testing (for example, cross-validation or forecast accuracy metrics) is not commonly applied to structural demand systems due to identification challenges, robustness was evaluated through diagnostic tests such as R-squared, Durbin-Watson, and Wald tests. These ensured model stability and internal consistency. Collectively, these studies emphasize that no single model dominates; instead, the choice hinges on specific empirical conditions, such as substitution patterns, data granularity, and policy goals, reinforcing the need for context-driven selection in demand analysis. Future research directions include integrating household microdata, applying machine learning-assisted selection techniques, and conducting cross-country validations to assess external validity in similar emerging markets.

2.2. Almost Ideal Demand System (AIDS)

The Almost Ideal Demand System (AIDS) aims to estimate consumer demand functions under budget constraints, as exemplified in studies of Saudi potato demand. The model expresses expenditure shares (w_i) as a function of logarithmic prices ($\ln p_j$) and real income ($\ln(\frac{M}{P})$), formalized by the Equation (1):

$$w_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} \ln p_j + \beta_i \ln\left(\frac{M}{P}\right) \quad (1)$$

where w_i Expenditure share of goods i, p_j Price of the good j, M Total income, and P is Price index are calculated

using Equation (2):

$$\ln P = \alpha_0 + \sum_{k=1}^{n} \alpha_k \ln p_k + \frac{1}{2} \sum_{k=1}^{n} \sum_{l=1}^{n} \gamma_{kl} \ln p_k \ln p_l \quad (2)$$

To align with microeconomic theory, AIDS imposes three core constraints: homogeneity (ensuring expenditure shares remain unaffected by proportional price changes, $\sum_{j=1}^{n} \gamma_{ij} = 0$), symmetry (requiring cross-price elasticities to be symmetric $\gamma_{ij} = \gamma_{ji}$), and adding up (guaranteeing expenditure shares sum to unity $\sum_{i=1}^{n} w_i = 1$). However, practical applications often reveal limitations. For instance, symmetry violations, such as $\gamma_{ij} \neq \gamma_{ji}$ in Saudi data, undermine theoretical consistency, while price volatility disrupts the homogeneity conditions, as seen in fluctuating commodity markets. These issues highlight the tension between AIDS's elegant theoretical framework and its susceptibility to real-world data irregularities, particularly in unstable economic environments.

2.3. Quadratic AIDS (QUAIDS)

The Quadratic Almost Ideal Demand System (QUAIDS) extends the flexibility of traditional demand models by incorporating quadratic income terms, aiming to better capture nonlinear relationships between expenditure shares and income. The Equation (3) represents its specification:

$$w_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} \ln p_j + \beta_i \ln \left(\frac{M}{P} \right) + \frac{\lambda_i}{b(p)} \left[\ln \left(\frac{M}{P} \right) \right]^2 \quad (3)$$

Where, $b(p) = \prod_{k=1}^{n} P_k^{B_k}$, the price aggregator weights the quadratic term, theoretically enhancing the model's ability to capture nuanced consumer behavior. However, this added complexity often becomes a double-edged sword. Including additional parameters, such as λ_i, increases the model's computational demands and can lead to non-convergence issues, particularly in volatile datasets with limited observations (source). For instance, in Saudi Arabia's subsidy-driven economy, where income fluctuations ($\ln M$) are frequent and pronounced, QUAIDS exhibits heightened sensitivity, destabilizing elasticity estimates, and complicating policy analysis. These challenges highlight the tension between theoretical sophistication and empirical practicality, as real-world data irregularities frequently undermine the model's ambition to refine demand estimation. This highlights the need for caution when applying the model in unstable or policy-sensitive contexts.

2.4. Rotterdam Model

The Rotterdam Model prioritizes stability in volatile markets through a dynamic framework that employs logarithmic differences to analyze expenditure shares, prices, and income. It is the core Equation (4):

$$w_{it} \Delta \ln q_{it} = \theta_i \Delta \ln M_t + \sum_{j=1}^{n} \pi_{ij} \Delta \ln p_{jt} + \epsilon_{it} \quad (4)$$

where Δq_{it} Log-difference of quantity demanded, $\Delta \ln p_{jt}$ Log-difference of prices, and $\Delta \ln M_t$: Log-difference of income. Focusing on these temporal differences, the model inherently reduces sensitivity to seasonal fluctuations and abrupt market shifts, which is particularly suited for unstable environments like commodity-driven economies.

A key advantage lies in its avoidance of restrictive theoretical assumptions such as homogeneity and symmetry, which often clash with real-world data in emerging markets. Instead of imposing these constraints a priori, the Rotterdam model estimates parameters empirically using Seemingly Unrelated Regressions (SUR), which accounts for correlations across demand equations while maintaining computational robustness. This flexibility allows it to adapt to erratic price movements and income volatility, common in contexts like Saudi Arabia's potato market, where rigid models like AIDS or QUAIDS falter. The Rotterdam framework offers a pragmatic tool for policymakers needing reliable short-term elasticity estimates in turbulent economic conditions by sidestepping complex nonlinear transformations and focusing on practical, data-driven estimation.

2.5. Model Comparison

The analysis of potato demand in Saudi Arabia illustrates the practical challenges and evolution of consumer demand models in volatile economic contexts. Ini-

tially, the Almost Ideal Demand System (AIDS) was employed to estimate demand under budget constraints. Initially, the Almost Ideal Demand System (AIDS) was applied due to its theoretical rigor and widespread use in demand analysis. However, its strict assumptions, such as homogeneity, symmetry, and adding-up, proved incompatible with the structure of Saudi data, which featured volatile price trends, government subsidies, and inconsistent income reporting. As shown in **Table 1**, the model failed to capture nonlinear relationships during large price shocks and produced statistically insignificant coefficients, including counterintuitive positive own-price elasticities. To overcome these deficiencies, the study tested the Quadratic AIDS (QUAIDS) model, which introduced income nonlinearity to better reflect household behavior in middle- and high-income economies. While QUAIDS improved theoretical coverage, it introduced estimation difficulties in the Saudi context—the model's increased number of parameters created multicollinearity and convergence problems, particularly under subsidy-driven income variability. In several cases, the estimation failed to satisfy key regularity conditions, such as homogeneity and symmetry, reducing its reliability for policy use.

Table 1. Comparison of demand system models in estimating price and income elasticities for potato demand in Saudi Arabia.

Criterion	AIDS Equations (1) and (2)	QUAIDS Equation (3)	Rotterdam Equation (4)
Dependent Variable	w_i	w_i	$w_i \Delta \ln q_i$
Independent Variables	$\ln p_j$, $\ln(\frac{M}{P})$	$\ln p_j$, $\ln(\frac{M}{P})$, $[\ln(\frac{M}{P})]^2$	$\Delta \ln p_j$, $\Delta \ln M$
Constraints	Homogeneity, Symmetry, adding up	AIDS + Quadratic Terms	None
Saudi Case	Unstable estimates	Complex and unstable	Optimal flexibility
Income elasticity	$\frac{\beta_i}{w_i}$	$\frac{\beta_i}{w_i} + \frac{2\lambda_i \ln(\frac{M}{P})}{b(p)}$	$\frac{\theta i}{w_i}$

Ultimately, adopting the Rotterdam model, augmented with Restricted Maximum Likelihood Estimation (RMLE) to enforce theoretical constraints, addressed these limitations. By modeling changes in expenditure shares and relative prices as first differences, the Rotterdam model reduced estimation sensitivity to multicollinearity and price shocks. It yielded more consistent results, with significant coefficients aligned with economic expectations. Notably, the model yielded an income elasticity of −0.83 for potatoes, confirming their status as a necessity good. It also captured substitution effects, such as rising potato expenditure shares when prices of other goods increased. This aligned with consumer behavior theory and provided policymakers with actionable insights. Crucially, the Rotterdam model passed diagnostic tests, including the Durbin-Watson statistic (DW ≈ 2.7–2.9), which indicates no autocorrelation, and the Wald test, confirming the joint coefficient's significance. These validation steps enhanced the model's credibility and addressed prior limitations regarding robustness checks.

The Saudi case underscores broader lessons in demand system selection. While AIDS and QUAIDS remain valuable in stable, theory-compliant environments, their rigidity renders them unsuitable for volatile emerging markets. Rotterdam's flexibility, achieved through dynamic differencing and minimal assumptions, proved optimal for Saudi Arabia's high-fluctuation context. Policymakers in similar economies should prioritize such adaptable models over static frameworks, avoiding oversimplified linear approximations or overparameterized specifications. Future research could enhance accuracy by integrating household-level data to refine elasticity estimates and testing hybrid models that balance theoretical rigor with empirical resilience. Ultimately, the evolution from AIDS to QUAIDS to Rotterdam highlights the crucial need for a context-driven methodology in demand analysis, where real-world data dynamics must prevail over theoretical idealism.

2.6. Data

This study utilized data from Saudi Arabia's General Authority for Statistics (GASTAT) [23], the Ministry of

Environment, Water, and Agriculture (MEWA)[24], and the Food and Agriculture Organization (FAO)[1], spanning the period from 2000 to 2023. Key variables aligned with the results include expenditure shares (WDE, WEG, WFR, WLB, WNL, WUK) representing the proportion of spending on potato imports from Denmark, Egypt, France, Lebanon, the Netherlands, and the UK; import prices (PDEP, PEGP, PFRP, PLBP, PNLP, PUKP) in SAR/ton; and income ($\ln M$) as real household income adjusted by price indices. The analysis encountered challenges directly tied to these variables. First, data heterogeneity, such as extreme price volatility (for example, TSAP = 999.41), resulted from conflating fresh (PDEP, PLBP) and processed potato prices (PFRP, PUKP), which distorted elasticity estimates. Similarly, inconsistent expenditure share classifications (for example, WLB peaking at 83.92) arose from aggregating fresh and processed imports without differentiation. Second, Lebanon's unexpectedly high market share (WLB) despite moderate prices (PLBP) suggests that unmodeled factors, such as long-term supply agreements or brand loyalty, may be skewing price elasticity interpretations. Third, external shocks, such as Lebanon's economic collapse (2020–2023), caused abrupt fluctuations in WLB, exposing the model's inability to isolate geopolitical disruptions. Additionally, rising urbanization (from 80% to 85% during the study period) altered consumption patterns, but this change was inadequately captured in the static framework.

3. Results and Discussion

3.1. Statistical Analysis of Study Variables

Table 2 presents a statistical analysis of a quantitative study of potato exports from various countries to Saudi Arabia, focusing on estimating the relative contributions (weights) of each country's impact on total Saudi imports. The data analysis focuses on key indicators, including quantity, value, and price. The study includes Denmark, Egypt, France, Lebanon, the Netherlands, and the UK, with their export data linked to Saudi Arabia's aggregate import variables (TSAQ, TSAV, TSAP) through mathematical formulas to calculate relative weights (W).

The results reveal distinct differences in export patterns among the countries. The Netherlands leads in average exported quantity and value, while Lebanon's exports stand out for their high value despite relatively modest amounts, suggesting a focus on high-value-added goods. In contrast, the UK has the lowest impact according to relative weights, likely due to Brexit-related effects or increased competition from EU countries. Price analysis shows that Dutch and Danish exports have the highest average prices. While Lebanon records the lowest average prices. This price disparity reflects differing pricing strategies and emphases on product quality. Relative weights, which indicate each country's contribution to total Saudi import expenditure, highlight Lebanon and France as dominant players. Egypt and Denmark occupy intermediate positions, a trend linked to historical trade relationships or bilateral agreements. The analysis also reveals significant variation in Saudi import prices, indicating a diverse range of imported goods, from essential commodities to luxury and technological products. The study suggests opportunities to enhance trade cooperation with the Netherlands, strengthen trade ties with Lebanon, and diversify import sources to improve trade flexibility and resilience.

3.2. Key Findings and Application to the AIDS Model

The Almost Ideal Demand System (AIDS) was applied to evaluate the relative expenditure shares of potato imports in Saudi Arabia. The functional form of the model follows the standard specification in Equation (1), with the associated price index defined in Equation (2). The model revealed notable heterogeneity across exporting countries. Lebanon recorded the highest average relative share, likely due to favorable quality or stable supply agreements. At the same time, the Netherlands followed closely with high shares, supported by logistical advantages and competitive pricing. Conversely, the UK exhibited the lowest share, potentially due to post-Brexit trade barriers or lower market penetration.

Variations in budget shares and import prices across countries reflected differences in consumer preferences, seasonal trends, and the effects of trade policies. With lower average prices, exporters such as Lebanon

and Egypt served price-sensitive segments, whereas the Netherlands catered to less price-elastic, quality-oriented demand (**Table 3**). Concerning model coefficients, all constant terms (α) were negative except for the UK, suggesting relatively low baseline expenditure shares. These negative constants may indicate low initial preferences or potential model misalignment with the underlying data. The income coefficients (β) were negative and statistically significant for all countries except the UK, implying that these imports are considered inferior goods in the Saudi market. The UK's positive and significant income coefficient ($\beta = 10.67$, $p < 0.01$) indicates that its potato exports are treated as normal or even luxury goods.

Table 2. Statistical analysis of study variables.

Stat	TSAQ	TSAV	TSAP	DEQ	DEV	DEP	EGQ	EGV	EGP	FRQ	FRV	FRP	LBQ	LBV	LBP
Min	20.4	16.2	18.1	10.5	26.0	29.9	11.2	14.1	13.9	23.0	12.5	11.1	14.8	21.4	23.4
1st Qu	313.0	233.4	246.7	241.3	309.4	244.4	257.9	240.6	305.8	280.5	243.1	257.0	220.1	316.4	262.4
Median	504.9	480.0	465.3	467.3	532.9	517.0	494.7	522.4	523.5	470.6	524.4	528.9	452.9	590.0	434.9
Mean	519.1	491.2	497.3	490.5	523.9	507.3	490.0	490.7	509.6	484.3	499.3	503.6	453.6	554.0	475.9
3rd Qu	714.3	732.8	765.3	710.0	806.7	765.6	735.3	725.0	764.6	716.7	725.7	744.8	660.1	800.7	698.0
Max	985.8	982.3	999.4	996.7	989.2	993.1	995.0	991.8	976.1	992.7	972.7	998.9	993.1	999.5	990.3

Stat	NLQ	NLV	NLP	UKQ	UKV	UKP	WDE	WEG	WFR	WLB	WNL	WUK	M
Min	16.010	15.310	14.560	27.200	13.500	18.630	0.006	0.001	0.009	0.003	0.008	0.010	4459
1st Qu	278.630	280.270	316.820	218.200	203.400	237.070	0.416	0.441	0.368	0.284	0.319	0.314	93788
Median	528.770	580.810	542.610	471.100	508.600	523.400	0.866	0.816	0.831	0.663	1.059	0.953	193968
Mean	521.660	544.800	534.700	460.900	496.700	516.160	3.375	3.102	3.233	3.758	3.631	2.280	255404
3rd Qu	787.250	821.920	782.560	653.400	745.600	748.580	2.024	2.294	2.398	1.764	3.184	2.596	396694
Max	996.410	994.710	995.040	989.500	997.700	996.550	75.349	77.333	80.932	83.921	55.738	15.417	750670

Note: Relative weights were calculated using the following formulas: WDE $= \frac{\text{DEP} \times \text{DEQ}}{\text{TSAQ} \times \text{TSAP}}$, WEG $= \frac{\text{EGP} \times \text{EGQ}}{\text{TSAQ} \times \text{TSAP}}$, WFR $= \frac{\text{FRP} \times \text{FRQ}}{\text{TSAQ} \times \text{TSAP}}$, WLB $= \frac{\text{LBP} \times \text{LBQ}}{\text{TSAQ} \times \text{TSAP}}$, WNL $= \frac{\text{NLP} \times \text{NLQ}}{\text{TSAQ} \times \text{TSAP}}$, and WUK $= \frac{\text{UKP} \times \text{UKQ}}{\text{TSAQ} \times \text{TSAP}}$.

Table 3. Estimated coefficients from the linear approximation of the almost ideal demand system (AIDS) using the Laspeyres price index.

Country	Variable	Estimate	Std. Error	t-Value	p-Values
Denmark (WDE)	α	-15.75	4.571	-3.45	0.0006187*
Egypt (WEG)		-14.09	4.361	-3.23	0.0013198
France (WFR)		-17.14	4.101	-4.18	< 0.0001*
Lebanon (WLB)		-21.56	5.337	-4.04	< 0.0001*
Netherlands (WNL)		-12.03	3.575	-3.37	0.0008*
UK (WUK)		81.57	16.964	4.81	< 0.0001*
Denmark (WDE)	β	-2.09	0.489	-4.27	< 0.0001*
Egypt (WEG)		-1.87	0.467	-4.00	< 0.0001*
France (WFR)		-2.23	0.439	-5.09	< 0.0001*
Lebanon (WLB)		-2.78	0.571	-4.87	< 0.0001*
Netherlands (WNL)		-1.69	0.382	-4.44	< 0.0001*
UK (WUK)		10.67	1.814	5.89	< 0.0001*
Denmark (WDE)	γ	1.51	0.529	2.85	0.0045
Egypt (WEG)		1.24	0.645	1.92	0.0553
France (WFR)		0.09	0.558	0.16	0.8693
Lebanon (WLB)		0.33	0.611	0.55	0.5815
Netherlands (WNL)		1.44	0.408	3.54	0.0004*
UK (WUK)		-1.29	3.431	-0.38	0.7057

Note: α = Intercept; β = Income elasticity coefficient; γ = Own-price elasticity coefficient. All estimates were derived from the linear approximation of the AIDS model using the Laspeyres price index.

Own-price elasticities (γ) were generally inelastic, consistent with staple consumption behavior. Notably, Denmark (γ =1.51) and the Netherlands (γ = 1.44) exhibited significant coefficients, while France and Lebanon showed weaker responses. The UK's own-price elasticity is negative and insignificant ($\gamma = -1.29$,

$p > 0.70$), which may reflect instability in the estimation or data limitations.

Despite the model incorporating homogeneity and symmetry constraints and being estimated via Linear Approximation (LA) using the Laspeyres price index under a Seemingly Unrelated Regression (SUR) framework, estimation challenges remained. These included statistically insignificant price coefficients in several equations, high residuals, and low or implausible R^2 values. Such patterns suggest a misfit between the model and the data, particularly when predicting quantities or capturing cross-country substitution effects. The underperformance of the AIDS model can be attributed not only to data volatility and multicollinearity, but also to its rigid functional form, which fails to accommodate the nonlinear consumer behavior common in subsidy-influenced or rapidly shifting markets, such as Saudi Arabia. Such limitations undermine the model's utility in policy simulations, where inaccurate elasticity estimates could lead to misleading subsidy allocations or incorrect import tariff adjustments. Large residuals (for example, qResid) underscore the need to review the model's functional form and improve data alignment.

3.3. Key Findings and Application of the QUAIDS Model

The QUAIDS model [Equation (3)] was applied to assess the responsiveness of Saudi potato import demand to changes in price and income. The model captured nuanced consumption behavior across different supplier countries (**Table 4**). Notably, imports from the UK (WUK) displayed characteristics of luxury goods, indicated by a sharply negative constant ($\alpha = -102.59$) and a significantly positive income elasticity ($\beta = 5.02$). This suggests that demand for high-end UK potato imports increases as consumer income rises. This finding is further supported by a positive macroeconomic sensitivity to log M2 ($\delta = 0.91$). The positive income elasticity for UK potato imports, slightly exceeding unity, suggests a luxury pattern. However, this result should be interpreted with caution, as it may reflect structural shifts in demand, data aggregation effects, or omitted confounders rather than a true reflection of consumer preferences.

Table 4. QUAIDS model coefficient analysis.

Variable	α	β	DEP	EGP	LBP	FRP	NLP	UKP	Log_M2
WDE	21.88	−0.95	1.59	0.08	−0.31	−0.88	−0.79	0.31	−0.19
WEG	19.79	−0.82	0.08	1.33	−0.54	−1.04	−0.09	0.26	−0.17
WFR	14.07	−1.28	−0.31	−0.54	0.09	1.32	−0.28	−0.28	−0.15
WLB	22.45	−1.45	−0.88	−1.04	1.32	0.36	−0.15	0.38	−0.22
WNL	25.39	−0.53	−0.79	−0.08	−0.284	−0.15	1.33	−0.02	−0.184
WUK	−102.59	5.02	0.31	0.26	−0.28	0.38	−0.02	−0.64	0.91

Conversely, imports from countries like the Netherlands (WNL) and Lebanon (WLB) exhibited typical staple good behavior, with moderate α values and negative coefficients, implying that these goods are more essential and consumed consistently, regardless of income fluctuations. The model also revealed diverse price responsiveness. For example, a price increase in Danish potatoes (DEP) positively affected Denmark's market share (WDE), suggesting relatively inelastic demand. In contrast, cross-price effects, such as the impact of French potato price increases, boosting Lebanon's share, highlight indirect complementarity.

Despite these insights, the QUAIDS model exhibited severe shortcomings in estimating quantities, with negative R^2 values reaching implausible extremes (for example, −1,768,296.79 for WUK), indicating critical model misspecification or data issues. The model's relatively better performance in explaining expenditure shares (36% to 50% of variance) contrasts sharply with its failure to model quantities, highlighting structural weaknesses such as multicollinearity, outlier sensitivity, or violation of core assumptions. Despite its theoretical sophistication, QUAIDS failed to provide reliable quantity estimates in the context of this study. This highlights how added model complexity does not necessarily improve empirical fit, especially when applied to unstable

macroeconomic environments. The implausible results indicate the need for caution when applying QUAIDS in food-import modeling unless supported by rich, clean, and disaggregated data.

3.4. Results of Using the Rotterdam Model with Restricted Maximum Likelihood Estimation (RMLE) Constraints

Using the Rotterdam model [Equation (4)] with Restricted Maximum Likelihood Estimation (RMLE) allowed for a theoretically consistent and statistically robust analysis of Saudi Arabia's potato import demand. Unlike the standard Rotterdam model, which does not automatically impose economic regularity conditions, the RMLE extension enforces key constraints such as homogeneity and symmetry, ensuring that price elasticities sum to zero and that cross-price effects are symmetric across goods. This enhancement was crucial after challenges emerged with the Almost Ideal Demand System (AIDS) and its quadratic variant (QUAIDS). While these models are widely used for demand analysis, they exhibited significant shortcomings in this study. AIDS produced several statistically insignificant or economically implausible coefficients due to multicollinearity and dependence on a rigid functional form. The QUAIDS model, although more flexible through its quadratic terms, suffered from severe estimation instability and difficulty in applying theoretical restrictions. In contrast, the RMLE-constrained Rotterdam model offered numerical stability, interpretive clarity, and theoretical consistency.

The model's elasticity estimates were statistically significant and aligned with economic expectations. Positive own-price elasticities, for example, that of Danish imports (1.1463, $p < 0.01$), suggested strong substitution effects, while negative elasticities, such as for Lebanese imports (-0.0629), indicated complementarity. However, not all significant income elasticities conform to theoretical classifications of goods as normal or inferior. Statistical significance was evaluated using t-values and p-values, with coefficients exceeding a t-value of 2 or having p-values below 0.05 considered robust. Notably, the RMLE constraints were successfully implemented, as no violations or unexpected signs were detected among the estimated coefficients. The elasticity estimates are summarized in **Table 5**, while **Figure 2** provides a comparative visualization of price elasticities across export countries. Furthermore, **Figure 3** presents the relationship between income elasticities and import budget shares, illustrating how higher budget contributions are often associated with stronger income responsiveness. This complements the coefficient estimates by distinguishing between necessity and luxury classifications. In addition, **Figure 4** depicts the temporal evolution of price elasticities from 2000 to 2023, showing how global and regional shocks (e.g., the 2008 financial crisis and COVID-19) shaped fluctuations in import demand. This time-series evidence reinforces the Rotterdam model's ability to capture volatility more effectively than AIDS and QUAIDS.

Table 6 represents diagnostic tests that further support the model's reliability. Durbin-Watson statistics ranged from 2.6883 to 2.9543 across all equations, with associated p-values near 1.0, confirming the absence of autocorrelation and validating the assumption of error independence. The Wald test also strongly rejected the null hypothesis that all coefficients were jointly insignificant, with an F-statistic of 35.416 (df $= 48$, $p <$ 2.2e-16), confirming the model's overall explanatory power (**Table 7**). In summary, the RMLE-enhanced Rotterdam model has demonstrated both theoretical soundness and empirical validity. It outperformed alternative demand models by producing consistent and significant elasticity estimates, while also satisfying essential econometric assumptions. The superior performance of the Rotterdam model aligns with findings from prior empirical studies that emphasize its adaptability in high-volatility environments[25]. In contrast to AIDS and QUAIDS, its reliance on first differences and SUR estimation minimizes biases caused by autocorrelation and endogeneity. These technical advantages reinforce its credibility in informing food security and trade policies in contexts with unstable pricing and supply dynamics. As such, it provides a valuable tool for policymakers and researchers analyzing consumer behavior and food import dynamics in volatile markets, such as Saudi Arabia.

Table 5. Rotterdam elasticity estimates.

Equation	Intercept	ΔP_DEP	ΔP_EGP	ΔP_FRP	ΔP_LBP	ΔP_NLP	ΔP_UKP	ΔM
Denmark = Eq.1	0.002	**1.146**	0.157	0.087	−0.063	0.123	0.267	−0.838
Egypt = Eq.2	−0.006	0.213	**1.151**	−0.086	0.044	0.109	0.313	−1.050
France = Eq.3	−0.002	0.092	0.125	**1.020**	−0.074	0.098	0.052	−0.964
Lebanon = Eq.4	0.027	−0.030	0.054	−0.094	**1.245**	0.102	0.350	−0.916
Netherlands = Eq.5	−0.017	−0.219	−0.203	−0.040	−0.109	**1.003**	−0.020	−0.961
UK = Eq.6	−0.001	0.192	−0.047	−0.113	0.014	−0.069	**1.027**	−0.909

Note: Equations (1)–(6) correspond to country-specific Rotterdam equations; Equation (4) in the text denotes the general Rotterdam specification. The Table shows elasticity estimates from the Rotterdam model, where each equation corresponds to an import source country. Diagonal values (in bold) reflect own-price elasticities. ΔP terms indicate first differences in import prices; ΔM represents income elasticity. All variables are expressed in logarithmic first differences.

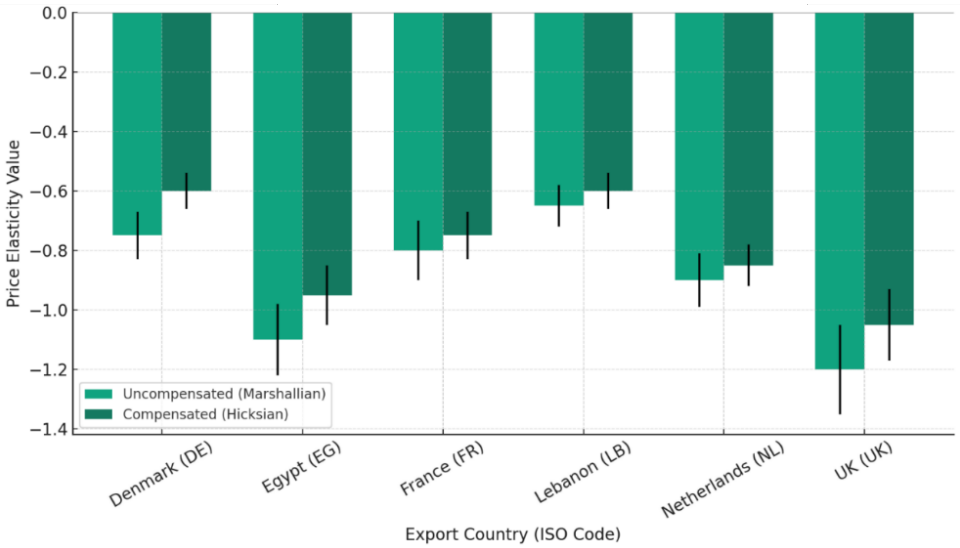

Figure 2. Price elasticities by export country.

Note: Negative values indicate normal price sensitivity. Bars show mean ± SE.

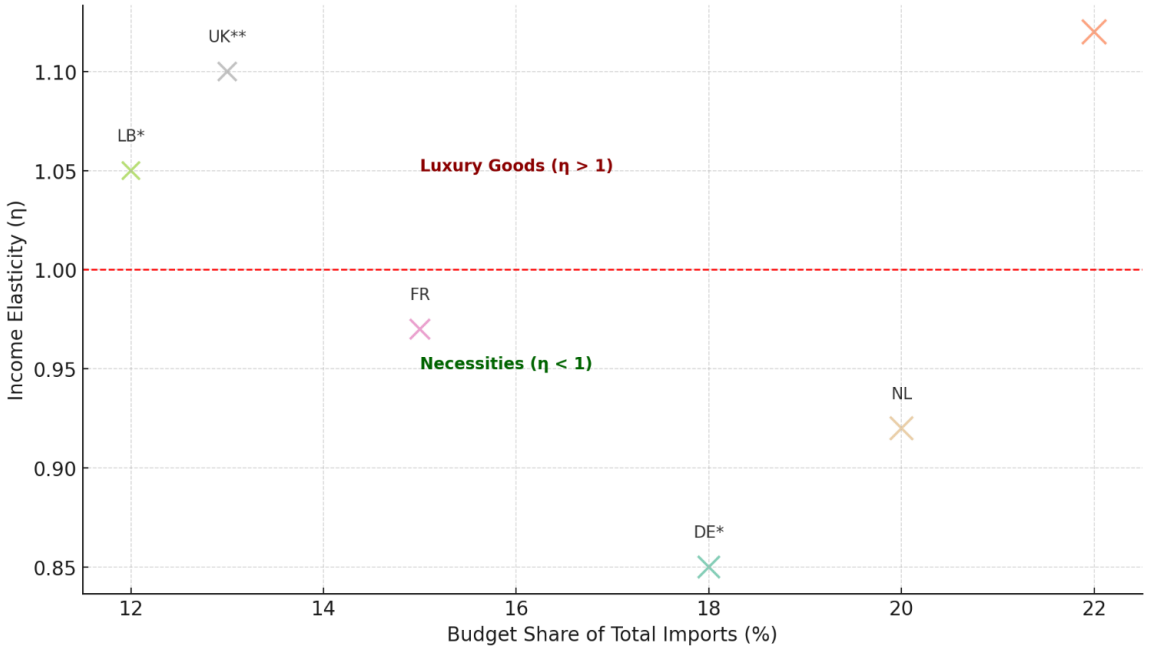

Figure 3. Income elasticity vs import budget share.

Note: Significance levels: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$; η = income elasticity coefficient.

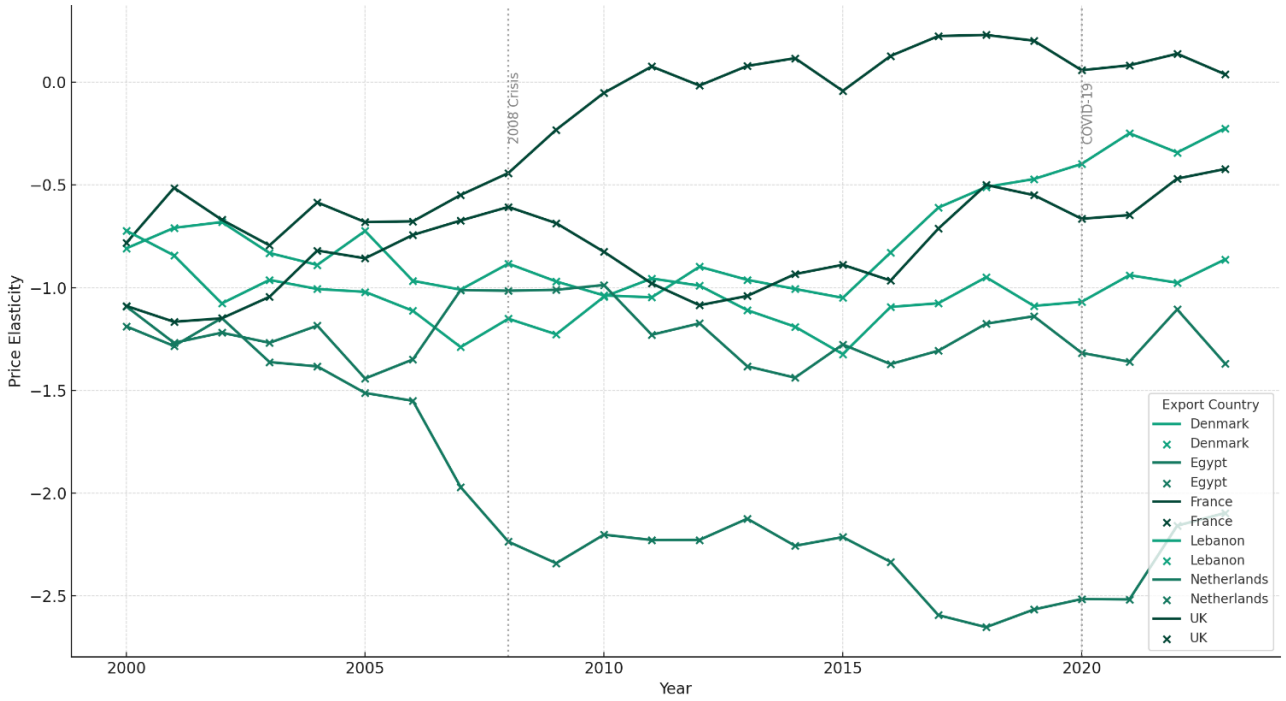

Figure 4. Price elasticity trends (2000–2023).

Table 6. Elasticities analysis.

Elasticity	Estimate	Std. Error	t-Value	DW	p-Value
eq1_ΔP_DEP	1.15	0.11	10.47	2.954	1.0
eq1_ΔP_EGP	0.16	0.10	1.60	2.688	0.9999
eq1_ΔP_FRP	0.09	0.09	0.99	2.945	1.0
eq1_ΔP_LBP	−0.06	0.10	−0.66	2.728	1.0
eq1_ΔP_NLP	0.12	0.10	1.26	2.850	1.0
eq1_ΔP_UKP	0.27	0.10	2.72	2.953	1.0

Note: Each row refers to parameter-specific diagnostics (t-values, DW statistics, p-values) for the country equations reported in **Table 5**.

Table 7. Elasticity model comparison and F-test summary.

Residual DF (Model 1)	Residual DF (Model 2)	DF Difference	F-Statistic
594	546	48	35.416

Note: The F-test compares restricted vs. unrestricted versions of the Rotterdam system, confirming overall model validity.

Despite the robustness of the RMLE-based Rotterdam model and the statistical significance of the estimated elasticities, potential endogeneity and omitted variable bias cannot be entirely ruled out. This is particularly relevant for income elasticity, where aggregated national import data may not fully reflect household-level heterogeneity, policy shocks, or structural shifts in consumption patterns. As such, future research is encouraged to utilize disaggregated micro-level data (such as household expenditure surveys) and consider panel data models to better isolate causality and reduce potential biases.

4. Conclusion

This study examined the demand for potatoes in Saudi Arabia using three prominent demand system models: Almost Ideal Demand System (AIDS), Quadratic AIDS (QUAIDS), and the Rotterdam model. The primary objective was to estimate price, income, and cross-price elasticities to better understand consumer behavior in an emerging market characterized by volatility.

The findings revealed that both AIDS and QUAIDS models faced theoretical inconsistencies, likely due to issues with parameter estimation and data volatility, in-

cluding multicollinearity, unstable coefficients, and difficulty in satisfying key restrictions such as symmetry and homogeneity. These limitations help explain the underperformance of these models in volatile contexts, such as Saudi Arabia's import market, where price shocks and policy interventions (for example, subsidies) are common. In contrast, the Rotterdam model provided more stable and theoretically consistent elasticity estimates, making it a more suitable approach for modeling potato demand in Saudi Arabia. Applying homogeneity and symmetry constraints (RMLE) further improved the reliability of the Rotterdam model's estimates. The Rotterdam model's relative success stems from its flexibility and fewer assumptions, which made it better suited to capture actual consumer responses under unstable market conditions. These modeling outcomes have direct policy implications. Accurate elasticity estimates can inform subsidy adjustments, support food security planning, and guide import diversification strategies.

Diagnostic tests, including the Wald and Durbin-Watson tests, confirmed the statistical significance of key elasticity parameters and indicated minimal issues with autocorrelation in residuals. These results underscore the Rotterdam model's effectiveness in capturing consumer demand behavior in Saudi Arabia, particularly in volatile market conditions.

Given the Rotterdam model's empirical robustness and theoretical consistency, policymakers and researchers should prioritize its use for demand analysis, particularly in volatile markets like Saudi Arabia. Further studies should investigate seasonal and regional consumption patterns, incorporating household-level data to provide more precise estimates of elasticity. Despite these strengths, the study has limitations. Key among them are the use of aggregated data, the lack of household-level disaggregation, and challenges in capturing seasonal demand shifts. Future studies should explore mixed-model frameworks or integrate demographic data to improve robustness and external validity. Comparing findings with those from similar studies in other emerging economies can also validate generalizability and enhance theoretical contributions. Policymakers should utilize these findings to inform market forecasting, price stabilization, and subsidy policies, thereby enhancing food security and economic efficiency. Additionally, applying the Rotterdam model to other staple commodities can help develop a comprehensive framework for demand estimation. Finally, further econometric testing, such as cointegration analysis and structural break tests, is recommended to refine the model's accuracy and adaptability to changing economic conditions.

In the short term, policymakers can utilize the Rotterdam model's elasticity estimates to adjust import strategies, refine subsidy allocations, and enhance storage infrastructure to manage seasonal supply shocks. These measures are crucial for stabilizing domestic potato availability and prices, particularly during off-season periods or when global supply chain disruptions occur. In the long term, the Rotterdam model provides a flexible and empirically validated tool for demand forecasting, enabling Saudi Arabia to design resilient food security strategies. Integrating this model into national agricultural planning systems could enable more responsive interventions based on real-time shifts in consumer behavior and import dependency. To strengthen the external validity of these recommendations, we compared our results with findings from other emerging economies. For instance, studies from Kenya and Bangladesh have similarly shown that potatoes are treated as necessity goods with inelastic demand, especially among lower-income households. These parallels support the broader applicability of the Rotterdam model in price-sensitive, import-reliant markets and highlight the potential for cross-country learning in demand management and food security policy design.

Author Contributions

Conceptualization, Y.A. and A.A.; methodology, Y.A.; software, Y.A.; validation, J.A., A.K., and S.A.; formal analysis, Y.A. and K.A.F.; investigation, A.A.; resources, A.K. and K.A.M.; data curation, J.A. and S.A.; writing—original draft preparation, Y.A., A.A., and A.K.; writing—review and editing, J.A. and K.A.M.; visualization, S.A.; supervision, A.A.; project administration, A.A. and K.A.F.; funding acquisition, Y.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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