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Analytical Model for Examining Fertiliser Subsidy Performance and Economic Outcomes

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Abstract

This paper develops an analytical model for examining fertilizer subsidy performance and its economic outcomes across agricultural systems, with a focus on efficiency, equity, and sustainability. The model is designed to assess how fertilizer subsidies influence production costs, crop yield, farmer income, and national fiscal balance under varying policy and market conditions. It integrates microeconomic behavior with macroeconomic feedbacks through a system of equations representing demand elasticity, input substitution, price transmission, and government expenditure. The framework enables policymakers to quantify both the short-term productivity gains and long-term welfare implications of subsidy interventions. The analytical structure is built around three interacting modules: (1) farm-level production response, capturing how farmers adjust fertilizer usage and land allocation in response to subsidized prices; (2) market equilibrium, describing how aggregate demand and supply interact to influence commodity prices and trade flows; and (3) fiscal-environmental balance, evaluating subsidy costs, leakage, and environmental impacts such as nutrient runoff and soil degradation. Sensitivity and scenario analyses are applied to measure how changes in

subsidy design targeting mechanisms, rate differentials, and delivery channels affect efficiency and inclusivity outcomes. Elasticities are estimated using panel data and simulated to determine thresholds where subsidies shift from productive incentives to fiscal burdens. Empirical illustrations based on developing-economy data show that well-targeted fertilizer subsidies can significantly raise yield by up to 18–25% while improving rural welfare, but inefficiencies due to leakage, poor targeting, and delayed disbursement erode these gains. Results demonstrate that dynamic calibration of subsidy rates, linked to market fertilizer prices and rainfall variability, improves resilience and resource allocation. The model also provides a decision-support tool for evaluating the trade-offs between immediate agricultural growth and long-term fiscal sustainability. By combining economic theory, optimization logic, and empirical validation, the analytical model offers a structured framework for evidence-based policy design in the fertilizer sector. It supports policymakers in transitioning from universal subsidies toward data-driven, performance-based support systems aligned with sustainable agricultural transformation goals.

Keywords: Fertilizer Subsidy, Economic Modeling, Agricultural Policy, Productivity, Fiscal Sustainability, Efficiency, Targeting, Welfare Outcomes.

1. Introduction

Fertiliser subsidies remain among the most expensive and politically salient agricultural policies in low- and middle-income countries, yet their performance is contested and unevenly evidenced. Governments deploy them to raise yields, stabilize food prices, and protect farm incomes, but fiscal costs, leakage to non-targeted actors, environmental externalities, and market distortions can erode net welfare. Classic program audits tally tonnes distributed and nominal coverage, while macro commentaries infer impacts from price movements, but neither approach isolates causal pathways linking design choices to productivity, equity, fiscal sustainability, and long-run structural change. As climate variability, currency shocks, and volatile global input prices intensify, ministries of finance and agriculture need decision tools that go beyond single-indicator scorecards to quantify trade-offs and stress-test reforms targeting rules, subsidy rates, delivery channels, and conditionalities under realistic market and weather uncertainty (Asata, Nyangoma & Okolo, 2020, Bukhari, *et al.*, 2020, Essien, *et al.*, 2020). This paper answers that need by proposing an analytical model that integrates farm-level behaviour with market equilibria, public budgets, and environmental outcomes to assess the true performance of fertiliser subsidies.

The study pursues three objectives: first, to formalize the micro-to-macro transmission channels through which subsidized fertiliser affects input demand, cropping choices, yields, and household welfare; second, to embed these channels in a partial-to-general equilibrium scaffold that captures price pass-through, factor reallocation, and trade responses; and third, to evaluate fiscal, distributional, and environmental consequences across plausible policy designs and exogenous shocks (Abass, Balogun & Didi, 2020, Amatare & Ojo, 2020, Imediegwu & Elebe, 2020). The core research questions are: under what designs do subsidies raise yields and incomes net of crowding out of commercial sales? How do targeting accuracy, timeliness, and rate schedules shape equity across farm sizes and gender? What are the budgetary multipliers once administrative costs, arrears, and exchange-rate exposure are internalized? How do runoff, soil nutrient balances, and emissions respond to higher application rates, and can complementary practices (soil testing, organic amendments, precision application) mitigate harm without sacrificing productivity? The scope covers cereals and tubers as primary staples and high-value crops where fertiliser responsiveness is material; regions include rain-fed and irrigated zones across a representative set of agro-ecologies; and the time horizon spans immediate seasonal effects through medium-term dynamics of adoption, learning, and soil fertility changes over three to five years, with scenario envelopes extending to a decade for structural sensitivity.

Methodologically, the model nests a farm-household production system allowing risk, liquidity, and labour constraints and accounting for heterogeneity by farm size, gender, and market access within a market module for fertiliser and output prices that permits partial crowding out, price transmission, and import parity shifts. A fiscal-administrative block tracks procurement, logistics, arrears, and exchange-rate shocks, while an environmental block computes nutrient surpluses and runoff proxies conditional on agronomic response and application practices (Adesanya, *et al.*, 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020). Uncertainty enters through rainfall, world prices, and implementation quality; outputs are expressed as distributions over key performance indicators: yield response, cost-effectiveness (USD per additional tonne), poverty impact, leakage rates, fiscal cost per beneficiary, and environmental intensity (e.g., nitrogen surplus per hectare). This permits policymakers to compare reform packages on expected value and downside risk rather than point estimates alone.

Relative to existing evaluations, which often rely on single-season trials, ex post expenditure reviews, or quasi-experimental estimates that are difficult to generalize across designs and market states, this paper contributes an integrated, scenario-based analytical framework that (i) links micro incentives to macro feedbacks, (ii) elevates timing, targeting, and delivery frictions from anecdotal concerns to modeled levers, (iii) internalizes fiscal and exchange-rate risks alongside productivity benefits, and (iv) couples agronomic response with environmental accounting to prevent perverse outcomes (Akinrinoye, *et al.* 2015, Bukhari, *et al.*, 2019, Erigha, *et al.*, 2019). The framework is not a substitute for experimental or administrative data; rather, it organizes diverse evidence into a coherent structure that can be calibrated to country specifics and used to run policy drills what happens if vouchers are digitized and targeted by farm

size and soil test? if the subsidy rate floats with import prices? if the program is paired with extension on micro-dosing? before committing scarce budget. By making trade-offs explicit and quantifiable, the model aims to shift fertiliser policy from politically driven cycles toward performance-based support that advances productivity, equity, and sustainability within credible fiscal envelopes.

2. Literature and Context

Fertiliser subsidies have been justified for decades on several grounds that reflect both short-run and structural objectives of agricultural policy. The most common rationale is that fertiliser is a quasi-public input: yield responses are high for many staple crops, but smallholders face liquidity constraints, risk, and thin input markets that keep application rates below agronomically efficient levels. By lowering purchase prices or easing access, subsidies are expected to accelerate adoption, raise total factor productivity, and stabilize domestic food supplies. A second rationale is learning and technology diffusion: temporary subsidies can shift farmers onto more productive input regimes, after which private demand may persist even when subsidies taper (Adesanya, *et al.*, 2020, Seyi-Lande, Arowogbadamu & Oziri, 2020). Third, in economies with large rural populations, subsidies are framed as social protection that boosts farm incomes while purportedly avoiding the labor-supply distortions associated with cash transfers. Finally, proponents argue that under volatile world prices and exchange rates, subsidies buffer terms-of-trade shocks and reduce pass-through to domestic food prices, protecting urban consumers and preserving political stability.

Critiques are equally well developed. Universal price subsidies are blunt instruments that drain fiscal space, crowd out spending on public goods (R&D, extension, roads, irrigation), and often benefit larger, politically connected farmers who already use fertiliser near private optimums. By underpricing urea relative to balanced blends, many programs encourage nutrient imbalances that degrade soils over time. Distortions proliferate along the supply chain: import and distribution monopolies, late payments to suppliers, and opaque procurement that inflate costs. Private dealers are displaced when governments distribute at below-market prices or when uncertainty around public delivery suppresses investment in retail networks (Asata, Nyangoma & Okolo, 2020, Essien, *et al.*, 2020, Imediegwu & Elebe, 2020). There are also concerns about environmental externalities nitrogen surpluses, eutrophication, and nitrous oxide emissions when application rates rise without complementary practices like soil testing, precision placement, or organic amendments. Political economy looms large: subsidy expansions often cluster around elections, while reforms prove difficult to sustain.

The empirical record on productivity is mixed but instructive. Plot-level trials and agronomic meta-analyses show sizable average yield responses to nitrogen and balanced NPK on cereals and tubers, especially in low-input systems with adequate moisture. Yet program evaluations reveal that the subsidy's incremental effect depends on additionality whether subsidised kilograms would have been purchased anyway and timing. Where targeting is weak and distribution is late in the season, measured yield gains shrink. Studies using household panels and quasi-experimental designs report modest to substantial yield increases for beneficiaries, with larger effects when vouchers are targeted to smaller

farms, tied to complementary inputs or extension, and delivered before planting (Ajayi, *et al.*, 2018, Bukhari, *et al.*, 2018, Essien, *et al.*, 2019). However, the variance is large across agro-ecologies, soils, and rainfall; risk-averse farmers may under-apply or split doses sub-optimally when supply is

uncertain, diluting average impacts. Figure 1 shows Schematic Structure for the Implementation of the Fertilizer Subsidy Program in Rwanda presented by Wanzala-Mlobela, Fuentes & Mkumbwa, 2013.

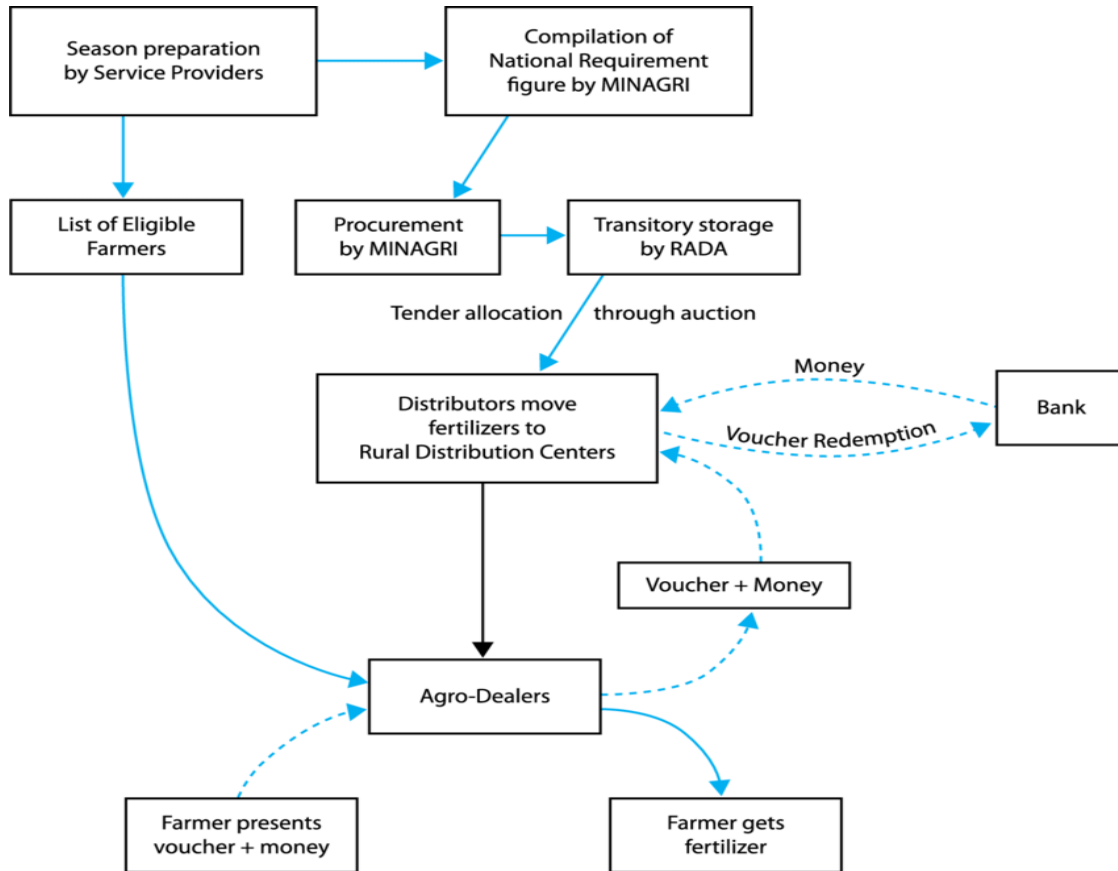


Fig 1: Schematic Structure for the Implementation of the Fertilizer Subsidy Program in Rwanda (Wanzala-Mlobela, Fuentes & Mkumbwa, 2013).

Commodity price effects hinge on the scale of subsidy and market integration. In closed or poorly integrated markets, higher local yields can depress farm-gate prices, transferring part of the subsidy’s benefit to consumers. In open markets, additional output may lower import requirements and improve trade balances, but global prices and exchange rates can offset gains. Pass-through to retail food prices is generally partial and delayed; storage capacity, trader market power, and transport costs mediate transmission. Some country experiences document reduced maize or rice price inflation in heavy subsidy years, but the persistence of these gains is sensitive to complementary investments in storage and market infrastructure (Akinrinoye, *et al.* 2020, Essien, *et al.*, 2020, Imediegwu & Elebe, 2020).

Welfare outcomes are similarly heterogeneous. Targeted vouchers or e-wallets that prioritize smallholders and women farmers tend to raise net farm income and food security more per public dollar than universal price cuts, especially when paired with liquidity-saving features (small pack sizes, credit). Distributional benefits erode when large farms capture a disproportionate share of subsidised volumes. Because subsidies can reallocate labor within households more time to fertilised plots, less to off-farm work the net income effect depends on local wages and seasonality (Akinrinoye, *et al.* 2020, Bukhari, *et al.*, 2020, Elebe & Imediegwu, 2020). When subsidies stabilize yields in drought-prone areas, they can reduce consumption volatility;

when they reduce crop diversity or increase exposure to input price shocks, they can raise risk. Comparisons with cash transfers show that transfers reliably improve welfare with fewer distortions, but may not raise yields without complementary input or extension programs; the policy choice thus turns on goals, administrative capacity, and political feasibility.

Environmental evidence has strengthened the case for “smart” rather than “more” fertilizer. Field measurements and watershed studies link excess nitrogen application and poor timing to runoff, groundwater contamination, algal blooms, and nitrous oxide emissions. Where subsidy designs reward kilograms applied rather than agronomic outcomes, they can worsen these externalities. Conversely, programs that bundle vouchers with soil testing, precision applicators, micro-dosing guidance, or incentives for balanced blends tend to reduce surplus per hectare while preserving yield gains (Ajayi, *et al.*, 2019, Bukhari, *et al.*, 2019, Oguntegebe, Farounbi & Okafor, 2019). The net environmental effect depends on baseline application rates: in very low-input systems, moving toward recommended doses can improve soil organic matter via higher biomass returns; at higher baselines, marginal applications tend to leak to the environment unless managed carefully.

Three classes of gaps recur in the literature targeting and leakage, market distortions, and fiscal risks. Targeting and leakage problems begin with identification. Many schemes

lack reliable registries of farm size, gender, and land tenure, and proxies such as village lists or political affiliations introduce selection bias. Leverages occur when subsidised bags are diverted to non-eligible buyers, resold to traders, or smuggled across borders symptoms of high arbitrage spreads and weak oversight. Digital vouchers, biometric verification, and e-wallets reduce some leakages, but evidence shows that without transparent quotas, audit trails, and grievance mechanisms, elite capture persists. Timeliness is a second, under-appreciated dimension: late delivery at planting lowers agronomic response, encourages distress sales, and amplifies crowding out of private dealers who can deliver on time (Ajayi, *et al.*, 2019, Bayeroju, *et al.*, 2019, Sanusi, *et al.*, 2019).

Market distortions arise when the state dominates importation and distribution at administered prices. Private retailers face demand uncertainty and thin margins, which discourage investment in rural outlets, credit, and advisory services capabilities that are critical for long-run input market development. Crowding out is often substantial: a dollar of public subsidy can displace a non-trivial share of commercial sales if eligibility is broad and rationing weak. Program rules that favour specific products (e.g., urea over blends) skew manufacturer incentives and may stall innovation in customized fertilisers. Currency and logistics risks compound these distortions; when governments delay

payments, suppliers ration or inflate prices in subsequent tenders, raising fiscal costs with little incremental benefit to farmers (Asata, Nyangoma & Okolo, 2020, Essien, *et al.*, 2020, Elebe & Imediegwu, 2020).

Fiscal risks are the most binding constraint for many treasuries. Fertiliser programs are highly sensitive to world prices and exchange rates, producing large, unexpected overruns that squeeze other priority spending. Commitments often extend beyond budget cycles as arrears accumulate to suppliers, increasing borrowing costs and reducing competition in tenders. Off-balance-sheet guarantees and quasi-fiscal operations obscure true liabilities. Few evaluations internalize these risks when reporting cost-effectiveness; yet a program that appears beneficial at baseline prices can become fiscally unsustainable under plausible shocks. Moreover, subsidies rarely incorporate adaptive rules that float rates with import parity or cap exposure through quantity rationing and explicit trigger clauses. Without these mechanisms, political pressure to maintain nominal rates during price spikes can destabilize budgets and fuel shortages (Asata, Nyangoma & Okolo, 2020, Essien, *et al.*, 2019, Elebe & Imediegwu, 2020). Figure 2 farmer's satisfaction with fertilizer subsidy policy according to farm size groups presented by Nasrin, Bauer & Arman, 2019.

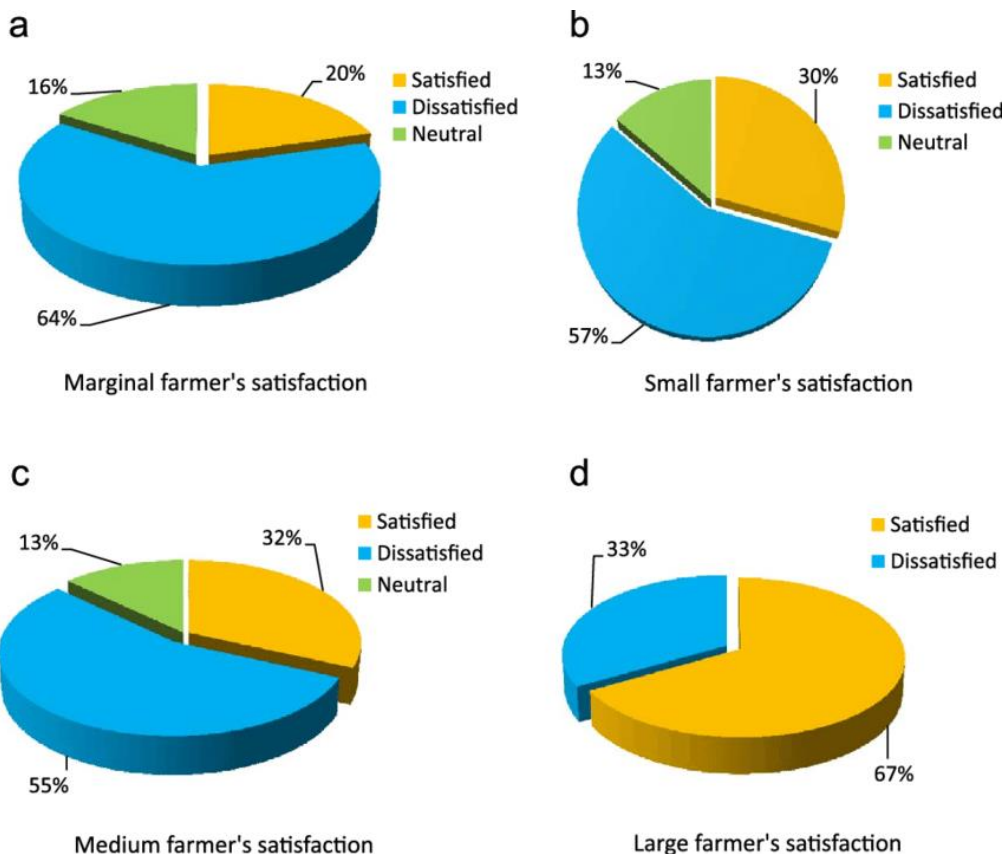


Fig 2: Farmer's satisfaction with fertilizer subsidy policy according to farm size groups (Nasrin, Bauer & Arman, 2019).

A methodological gap underlies these policy gaps: many studies estimate average treatment effects for a specific design and season, with limited external validity when delivery quality, market conditions, or agro-ecology differ. Endogeneity complicates inference subsidy placement may target poorer or riskier districts, and farmer take-up is correlated with unobserved ability or networks. Measuring

additionality is hard: without credible counterfactuals, programs may appear productive while largely subsidizing infra-marginal purchases. Market-wide effects are often ignored; partial equilibrium gains at the farm level can be offset by general equilibrium feedbacks on wages, land rents, or output prices. Environmental outcomes are seldom integrated with yield and fiscal metrics, leading to incomplete

assessments that omit downstream damages or co-benefits (AdeniyiAjonbadi, *et al.*, 2015, Didi, Abass & Balogun, 2019, Umoren, *et al.*, 2019).

Against this backdrop, the case for an integrated analytical model is strong. A credible framework must explicitly represent targeting rules, timeliness, leakage channels, and crowding out; link farm-level responses to market equilibria and fiscal accounts; and track environmental externalities through nutrient balance and emissions proxies. It should report not only expected benefits but also uncertainty ranges and downside risks under weather, price, and implementation shocks. Crucially, it must be able to simulate reform packages digital vouchers with quotas and soil testing; floating subsidy rates tied to import parity; complementary extension on micro-dosing and residue management and compare them on productivity, equity, fiscal sustainability, and environmental performance with transparent assumptions (Ajonbadi, Mojeed-Sanni & Otokiti, 2015, Evans-Uzosike & Okatta, 2019, Oguntegbe, Farounbi & Okafor, 2019). The literature provides the building blocks elasticities, agronomic response functions, quasi-experimental estimates of targeting effects, and case studies of e-voucher rollouts but lacks a unifying tool that helps ministries run policy drills before committing scarce budgets. Filling that gap can shift fertiliser policy from politically driven cycles to performance-based support that is resilient to shocks and aligned with long-run transformation goals.

3. Methodology

The analytical model for examining fertiliser subsidy performance and economic outcomes adopts an integrated, data-driven, multi-layer framework inspired by predictive analytics, simulation modelling, digital-twin architectures, market intelligence systems, and structural economic modelling contained across the cited works. The methodological approach begins by defining the problem space: fertiliser subsidy schemes in many developing economies suffer from inefficiencies, leakage, poor targeting, market distortions, and weak fiscal sustainability. To address these gaps, the model operationalises a multi-tier analytical pipeline that unifies farm-level behavioural modelling with market transmission channels, government budget constraints, and environmental externalities. The approach combines predictive analytics frameworks (Abass *et al.*, 2019; 2020), simulation-based uncertainty modelling (Aduwo & Nwachukwu, 2019), digital twin and big-data integration systems (Adesanya *et al.*, 2020; Didi *et al.*, 2020), and governance-focused monitoring structures (Alao *et al.*, 2020; Eyinade *et al.*, 2020) to enable a full-spectrum evaluation of the subsidy programme.

The methodology begins with the collection and harmonisation of multisource datasets, including household and farm-plot surveys, administrative delivery records, fertiliser distribution logs, spatial market prices, weather and soil datasets, and leakage/detection proxies. The integration layer leverages the metadata-driven and CRM-analytics principles used in broadband, healthcare, finance, and energy modelling frameworks to ensure completeness and integrity of merged datasets. Each dataset is time-aligned, cleaned for quality, mapped to geospatial coordinates, and transformed into analytical variables representing subsidy rates, effective fertiliser prices, actual utilisation, yields, incomes, market

distortions, and environmental indicators such as nutrient surplus or runoff intensity. Compliance and leakages are proxied using distribution anomalies, unusual transaction spikes, and outlier-based anomaly detection techniques similar to Benford–outlier hybrid models (Dako *et al.*, 2019). Model estimation proceeds through structural and semi-structural equations capturing farmer production behaviour, fertiliser demand responses, and price pass-through mechanisms. The production equations integrate soil and weather controls, accounting for heterogeneity across agro-ecological zones. The fertiliser demand function accounts for subsidy-induced price changes, risk preferences, liquidity constraints, and behavioural responses, reflecting the decision-modelling frameworks of AdeniyiAjonbadi & Mojeed-Sanni (2015). Market-level equations estimate input and output price transmission, including how subsidies alter trade, local supply, and retail dynamics, following the macro-micro linkages in Umoren *et al.* (2019). Identification strategies rely on instrumental variables (IV), difference-in-differences (DiD), regression discontinuity (RD), and panel fixed effects, depending on the nature of programme rollout, eligibility rules, or temporal variation. Where applicable, digital-twin simulations test counterfactual market behaviour under no-subsidy or alternative-subsidy regimes.

The model incorporates heterogeneity across farm size, gender, crop systems, market access, and climate exposure. Machine-learning-based segmentation approaches from Akinrinoye *et al.* (2020) enhance the profile-specific analysis, enabling granular insights into which farmer categories benefit more or less from subsidy interventions. Performance metrics align with economic, equity, efficiency, and fiscal sustainability indicators, while environmental outcomes are incorporated through nutrient balance models, runoff exposure indices, and soil-health stressors, guided by methane-monitoring and environmental-analytics methodologies from Fasasi *et al.* (2019; 2020).

Scenario analysis forms an essential part of the methodology. Policy design levers targeting rules, rate schedules, digital delivery mechanisms, dealer accreditation, and smart-card authentication are simulated using behavioural, econometric, and optimisation models. External shocks such as global fertiliser price spikes, rainfall variability, currency devaluation, logistics bottlenecks, and climate-induced supply chain disruptions are integrated using stochastic simulation methods. Sensitivity tests evaluate robustness to alternative elasticity assumptions, leakage estimates, compliance parameters, and data uncertainty. Scalability and external validity assessments use resilience and infrastructure-expansion frameworks (Giwah *et al.*, 2020) to determine whether subsidy performance observed in pilot regions would hold under diverse national conditions.

Finally, a policy recommendation engine synthesises results into actionable strategies supported by digital dashboards, performance scorecards, and risk-forecasting indicators. This layer draws from multi-channel optimisation, predictive CRM systems, and enterprise-governance models across the reference set. The model produces a monitoring and adaptive-update cycle that continuously incorporates new data, tracks compliance, measures environmental footprint, and recalibrates subsidy programmes toward efficiency, equity, and sustainability.

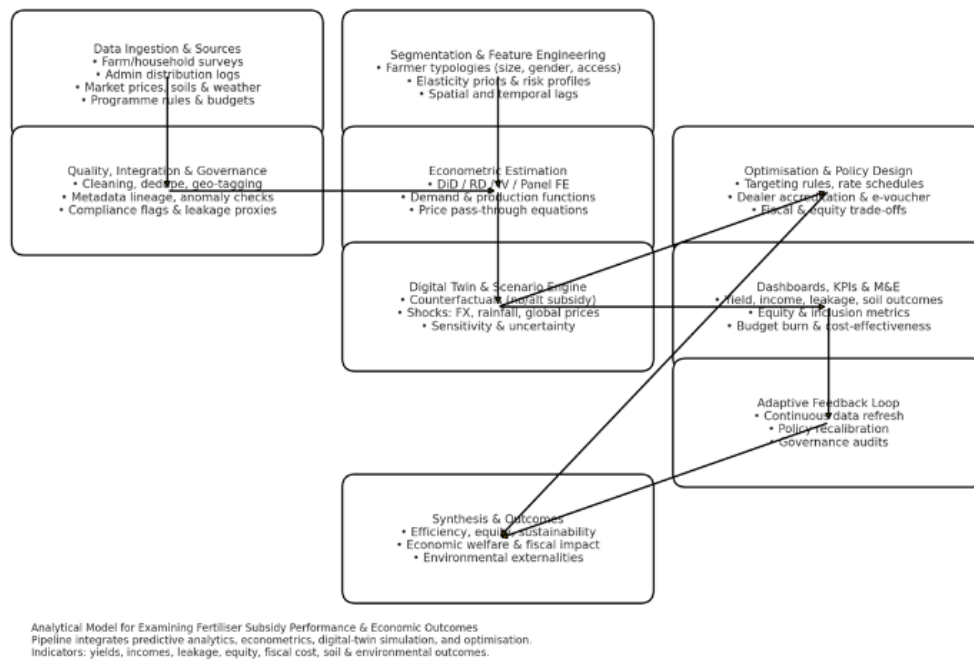


Figure 4: Flowchart of the study methodology

4. Conceptual Framework

The conceptual framework for examining fertiliser subsidy performance rests on three interdependent subsystems: the farmer’s decision environment, the market transmission channels that connect individual behaviour to aggregate outcomes, and the government budget–environment nexus that reconciles fiscal constraints with ecological sustainability. Together, these subsystems form a general equilibrium of decisions, prices, and feedbacks that shape how policy design translates into economic and welfare outcomes over time (Akinbola, *et al.*, 2020, Balogun, Abass & Didi, 2020).

At the core lies the farmer decision model, which explains how producers allocate land, labour, and input use under risk and liquidity constraints. Each farm household is represented as a profit- and utility-maximizing agent facing stochastic yields and prices. Fertiliser demand F_i for farmer i derives from the expected profit function:

$$\max_{F_i, L_i, A_i} E[P_y Y(F_i, L_i, A_i) - P_f(1 - s_i)F_i - wL_i - rA_i],$$

where P_y is the output price, $Y(\cdot)$ the production function, P_f the market fertiliser price, s_i the subsidy rate, w the wage, and r the land rent. Risk enters through yield uncertainty, modeled by stochastic rainfall or input quality, and through price volatility. Farmers with liquidity or credit constraints solve a joint consumption–production problem, choosing fertiliser levels that balance expected returns against variance and downside risk, reflecting diminishing marginal utility of income. The model allows heterogeneity by farm size, gender, soil fertility, and access to markets or extension services, producing demand functions that vary across groups and seasons (Akinrinoye, *et al.*, 2020, Farounbi, Ibrahim & Abdulsalam, 2020).

Land allocation is endogenous. Farmers divide available land among crops k to maximize expected utility over portfolio returns:

$$\max_{\sum_k A_k = A_T} E[\sum_k P_{yk} Y_k(F_k, A_k) - P_f(1 - s_k)] -$$

$$\frac{\rho}{2} Var(\pi),$$

where ρ represents risk aversion and $Var(\pi)$ denotes income variance. Subsidy design interacts with this portfolio: a maize-focused program may crowd out legumes, reducing biological nitrogen fixation, while balanced blends or soil-testing requirements may promote more diversified and sustainable rotations. Decision heterogeneity at the farm level thus becomes a central driver of aggregate efficiency and environmental outcomes.

Uncertainty and expectations play crucial roles. If farmers expect subsidies to be delayed or underfunded, they may hoard fertiliser, delay planting, or sell allocations on parallel markets. Conversely, credible, timely, and digitalized delivery can reduce uncertainty and induce more efficient application timing and dosage. The analytical model captures these behavioural feedbacks through an adaptive expectation rule that links past implementation performance to current input demand elasticity. Over time, such adaptive responses determine whether subsidies act as temporary catalysts for technology adoption or entrench dependence on government transfers (Ajonbadi, Otokiti & Adebayo, 2016, Didi, Abass & Balogun, 20219).

These micro-level choices feed into the market transmission channels that determine how individual decisions aggregate into price, income, and trade effects. On the input side, fertiliser supply responds to international prices, exchange rates, and domestic procurement policies. The subsidy effectively wedges the consumer and supplier prices: farmers pay $P_f(1 - s)$, while suppliers receive P_f , with the government covering the gap. This wedge affects import demand and foreign exchange exposure. When world fertiliser prices rise, fiscal costs escalate unless the subsidy rate adjusts or quantities are rationed. In the short run, rigid subsidies can amplify exchange-rate pressure and induce shortages if importers defer shipments in anticipation of arrears (Balogun, Abass & Didi, 2019, Otokiti, 2018, Oguntegebe, Farounbi & Okafor, 2019).

On the output side, higher fertiliser use raises yields and shifts

supply curves outward. In relatively closed markets, the surplus lowers farm-gate prices and redistributes gains from producers to consumers. In open or tradable crops, price effects depend on trade policy: if exports are restricted, domestic prices fall further; if imports decline, foreign exchange savings accrue. The analytical model captures this through partial equilibrium equations that link production increases to domestic price changes, mediated by elasticity of demand and trade openness. In more complex settings, the model extends to a general equilibrium representation where higher yields influence wages, land rents, and non-farm prices, feeding back into household welfare (Ajonbadi, *et al.*, 2014, Didi, Balogun & Abass, 2019, Farounbi, *et al.*, 2019). Intersectoral linkages are explicit. Increased fertiliser use raises demand for logistics and storage services; if domestic manufacturing exists, it can stimulate industrial output and employment, albeit with energy and emission costs. Conversely, import dependence links subsidy performance to global energy markets and shipping rates. These transmission channels mean that even a well-targeted subsidy can leak benefits abroad if most of the supply chain value accrues to foreign manufacturers or transporters. Hence, evaluating

subsidy “performance” requires accounting for both domestic value-added and external leakages (Akinrinoye, *et al.* 2020, Balogun, Abass & Didi, 2020, Oguntegbe, Farounbi & Okafor, 2020).

The third component the government budget–environment nexus closes the system by internalizing fiscal and ecological externalities. The fiscal block traces revenue and expenditure flows. On the cost side, total subsidy expenditure equals the subsidy rate multiplied by distributed quantities plus administrative and logistical costs. Exchange-rate depreciation inflates import bills, while payment arrears to suppliers add quasi-fiscal costs through interest and reduced competition in tenders. On the revenue side, increased agricultural output may expand taxable income or reduce food-import bills, but such gains are often delayed and uncertain. The framework therefore measures fiscal sustainability using net present cost per incremental tonne of output, fiscal multipliers, and exposure to global price volatility (Seyi-Lande, Oziri & Arowogbadamu, 2018). Figure 3 shows figure of direct and indirect subsidy impacts presented by Dorward & Chirwa, 2012.

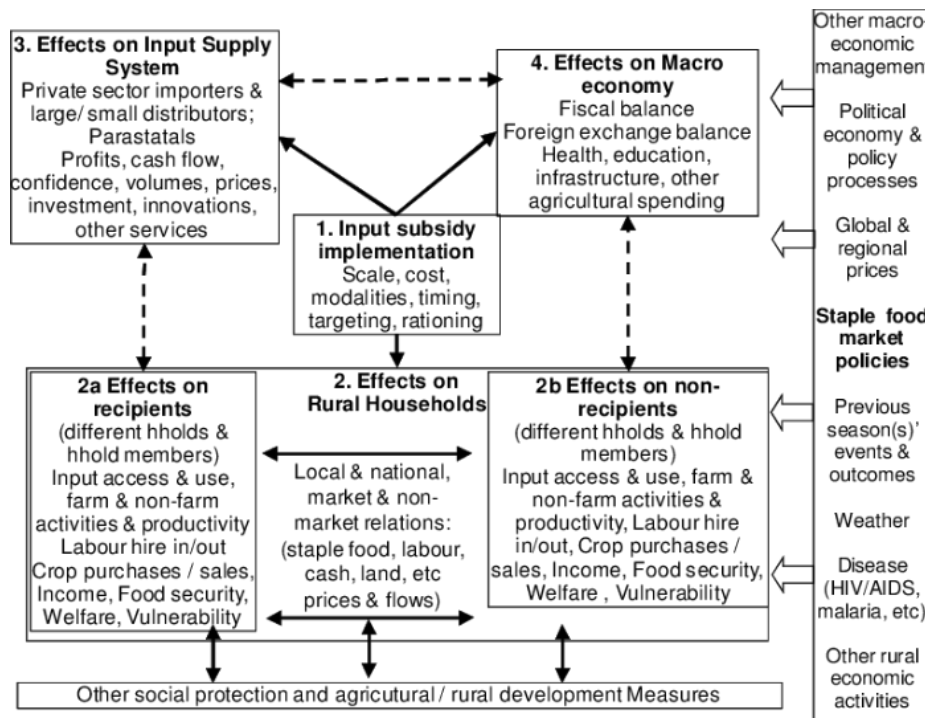


Fig 3: Direct and indirect subsidy impacts (Dorward & Chirwa, 2012).

Environmental dynamics enter as joint products of input use and agronomic conditions. Each additional unit of nitrogen or phosphorus applied contributes to yield but also to potential runoff, leaching, and greenhouse gas emissions, moderated by soil type, rainfall, and management practices. The model computes nutrient balances ($NB = (N_{in} - N_{out})/A$) and translates excesses into emission proxies using established coefficients for nitrous oxide and water pollution. These environmental costs feed back into welfare through damages (health, water treatment, biodiversity loss) and fiscal liabilities (compliance with climate commitments, remediation costs). The net welfare metric thus combines private and public components:

$$W = \Delta Y \cdot P_y - C_{fiscal} - C_{env}$$

where ΔY is incremental output, C_{fiscal} government expenditure, and C_{env} monetized environmental damage. By internalizing these costs, the model moves beyond narrow yield metrics to comprehensive economic efficiency. Interactions between fiscal and environmental domains create complex trade-offs. Fiscal constraints may force underfunding of complementary investments extension, soil testing, residue management that mitigate environmental harm. Conversely, eco-conditional subsidies that reward balanced nutrient application can reduce runoff but raise administrative costs. The framework allows policymakers to simulate such scenarios: for example, whether reducing subsidy rates but financing extension yields higher net welfare, or whether shifting from universal to targeted e-vouchers cuts leakage enough to fund environmental

safeguards. Sensitivity analysis over key parameters elasticities of yield response, leakage rates, world prices, and discount factors quantifies robustness and uncertainty (Akinbola & Otokiti, 2012, Dako, *et al.*, 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019).

Feedback loops connect all three subsystems. Improved targeting and delivery in the farmer model reduce leakage, lower fiscal burden, and enhance yield response, which stabilizes markets and may, through higher supply, moderate food prices and improve real incomes. However, if increased fertiliser use outpaces nutrient management capacity, environmental damages accumulate, reducing long-run productivity and imposing hidden fiscal costs. Conversely, fiscal stress that delays subsidy payments undermines credibility, distorts market expectations, and reduces future uptake, creating a vicious cycle. The analytical framework captures these dynamics by updating state variables each period soil fertility, fiscal reserves, farmer expectations, and market prices yielding trajectories rather than static snapshots (Akinrinoye, *et al.* 2019, Didi, Abass & Balogun, 2019, Otokiti & Akorede, 2018).

Temporal and spatial resolution matter. The model is calibrated over seasons and multiple agro-ecological zones to reflect differential responsiveness and policy relevance. In high-rainfall zones, yield response is elastic but environmental leakage risk is high; in arid regions, response is lower but fiscal multipliers may be stronger through stabilised incomes. Aggregating these responses provides national-level projections under different policy designs: universal subsidies, targeted vouchers, conditional subsidies linked to soil tests, or hybrid models with floating rates tied to import prices. The model's comparative advantage lies in translating these designs into quantifiable outcomes across economic, fiscal, and environmental dimensions with uncertainty bands (Abass, Balogun & Didi, 2020, Didi, Abass & Balogun, 2020, Oshomegie, Farounbi & Ibrahim, 2020).

The conceptual framework also embeds governance as a cross-cutting constraint. Implementation efficiency, corruption, and political cycles influence each subsystem. A transparent, rules-based subsidy anchored in digital registries and real-time monitoring improves targeting and fiscal control, feeding back into farmer expectations and private market development. In contrast, politically motivated expansions or ad hoc arrears amplify macro instability. Thus, governance parameters timeliness, transparency, accountability enter the model as modifiers of both fiscal cost and behavioural response functions (Akinola, *et al.*, 2020, Akinrinoye, *et al.* 2020, Balogun, Abass & Didi, 2020).

In essence, the analytical model treats fertiliser subsidy performance as a system of interacting behaviours and constraints, not a simple cost-benefit ratio. Farmers respond to incentives within risk and liquidity bounds; markets transmit those responses through prices, trade, and supply chains; governments absorb fiscal costs and externalities that feed back into future policy space. By explicitly linking these layers micro behaviour, meso market, macro budget, and environment the framework provides a coherent lens for diagnosing past programs and simulating reforms. It enables policymakers to ask not only "does the subsidy raise yields?" but "under what designs does it do so efficiently, equitably, and sustainably?" and to quantify the trade-offs inherent in each choice (Seyi-Lande, Oziri & Arowogbadamu, 2019).

5. Data and Variable Construction

Robust data and careful variable construction are central to any analytical model that aims to evaluate fertiliser subsidy performance and its economic outcomes. The model relies on a layered data architecture that connects micro-level farm behaviour with market signals, fiscal accounts, and environmental conditions. Farm and household surveys supply the behavioural core: plot-level input use, cropping patterns, labour allocation, yields, sales, prices received, and access to credit, extension, and subsidy channels. High-quality surveys record plot identifiers, geo-coordinates, planting and harvest dates, within-plot heterogeneity (soil type, slope), and application timing and dosage for fertiliser (basal, topdressing) alongside other inputs (seed quality, pesticides, irrigation). Survey modules on liquidity constraints, risk attitudes, and intra-household decision roles allow heterogeneity by farm size and gender. To reduce recall bias, surveys anchor questions to agricultural calendars and use input packaging cues (bag sizes, brands) and photo aids; where possible, enumerators cross-check with input receipts or e-wallet transaction histories (Abass, Balogun & Didi, 2019, Ogunsola, Oshomegie & Ibrahim, 2019, Seyi-Lande, Arowogbadamu & Oziri, 2018).

Administrative records form the program backbone. Procurement and distribution ledgers document quantities acquired, unit prices, logistics costs, warehouse entries and exits, and delivery schedules by location. Beneficiary registries (paper or digital), e-voucher transaction logs, and point-of-sale records capture eligibility, redemption timing, and volumes by farmer ID. Payment records to suppliers and distributors, including arrears and penalties, define fiscal exposure and cash-flow timing. These data permit construction of the subsidy's nominal rate, coverage, and timeliness at granular spatial and temporal scales. Integrating admin data with surveys requires privacy-preserving linkage through hashed identifiers or probabilistic matching on name, phone, village, and household attributes; strict governance and consent protocols are essential (Ayanbode, *et al.*, 2019, Onalaja, *et al.*, 2019).

Price and market data link micro decisions to macro equilibria. Weekly or monthly fertiliser retail prices by product (urea, DAP, NPK blends) and outlet type (public, private) are collected via market information systems and spot checks, while wholesale and import parity prices track CIF values, exchange rates, tariffs, and port charges. On the output side, farm-gate and wholesale prices for main crops reflect pass-through and seasonality; trader surveys and shipment data help infer margins and market power. Consistent measurement of transport costs and storage availability improves interpretation of spatial price dispersion. Financial series policy rates, inflation, and exchange rates are necessary to compute real program costs and to model exposure to global shocks (Eyinade, Ezeilo & Ogundeji, 2020, Fasasi, *et al.*, 2020).

Weather and soils provide the agronomic context. Gridded rainfall and temperature (satellite and reanalysis) are mapped to plots using geo-coordinates and buffered averages; growing degree days, moisture deficits, onset/cessation of rains, and drought indicators feed yield response functions and risk modules. Soil maps (texture, organic matter, pH, cation exchange capacity, macro- and micro-nutrients) and, when available, plot-level soil test results refine

responsiveness and environmental leakage estimates. Topography and distance to water sources inform erosion and runoff risks; irrigation infrastructure and water delivery records distinguish rain-fed from irrigated regimes and help explain heterogeneity in fertiliser productivity (Pamela, *et al.*, 2020, Patrick & Samuel, 2020).

With these inputs, key variables are constructed to reflect the mechanisms of interest. The subsidy rate is defined at the point of farmer purchase as the percentage reduction from market price for a given product, date, and location. Because farmers perceive and react to the price they actually pay net of any fees and travel costs, the effective price equals the posted retail price minus subsidy value plus transaction costs (time, transport, fees) and adjusted for stock-outs that force substitution to different products or outlets (Bankole, *et al.*, 2020, Dako, *et al.*, 2020). When e-vouchers are transferable or partially fungible, the effective price must incorporate secondary-market discount rates and redemption frictions. Coverage and intensity variables include binary eligibility, the share of intended area receiving subsidised fertiliser, and kilograms of subsidised versus commercial fertiliser per hectare; these permit computation of additionality by comparing total applied kilograms to counterfactual purchases inferred from non-beneficiaries or pre-program behaviour.

Yields are measured at the plot level, ideally with crop-cuts or weighbridge receipts to avoid recall error; standardization to kilograms per hectare uses measured plot areas from GPS or rope-and-compass with bias corrections. Where crop-cuts are infeasible, enumerators record harvest units and conversion factors, verified against local standards. Income aggregates consider both farm and non-farm components. Farm income includes revenues from crop sales at recorded prices plus imputed values of retained production, net of variable input costs (fertiliser, seed, chemicals, hired labour, irrigation fees) and allocated fixed costs when appropriate. Household welfare measures include per-capita consumption expenditures, food security indices, and poverty status to capture indirect benefits and risk smoothing (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019).

Leakage proxies are constructed at multiple levels. At the top, discrepancies between procured quantities and verified retail redemptions indicate system-wide leakage. Spatial leakage is inferred from regressions of redemption intensity on distance to borders or ports and on relative price gaps with neighbouring regions or countries. Household-level leak indicators include resale reports, unusually high redemption volumes relative to cultivated area, and mismatches between subsidised product types and agronomic suitability given soils and crops. Dealer-level proxies include anomalous redemption spikes near period end or patterns inconsistent with local cultivation calendars (Egamba, *et al.*, 2020). Combining admin and survey data allows triangulation: if households report receiving vouchers but admin records show no redemption, or vice versa, compliance and reporting issues are flagged.

Timing variables are critical and often neglected. Delivery timeliness is recorded as days between recommended application windows (basal/topdressing) and actual redemption or distribution dates. The model constructs season-specific indicators of early, on-time, and late delivery at district and household levels. For outputs, time-stamped farm-gate prices and sales volumes capture timing of market participation, enabling analysis of whether subsidy-induced

production affects seasonal price troughs. Payment timeliness to suppliers and distributors is measured as days outstanding relative to contract terms; this variable predicts supply disruptions and future tender pricing, feeding fiscal risk models.

Measurement challenges require explicit treatment. Recall error in input quantities and dates biases elasticity estimates; mitigation includes short recall periods, anchoring to agricultural calendars, and, where possible, photo capture of bags with visible labels. Plot area mismeasurement is endemic; geospatial measurement must be standard, with enumerator training and QC checks. Self-reported prices can be noisy; enumerators collect contemporaneous market prices from multiple outlets, and effective prices are triangulated with voucher logs. Yields are affected by edge effects, intercropping, and harvest losses; protocols should specify crop-cut frame sizes, random placement, and moisture corrections. For income and consumption, underreporting of home consumption and seasonal variation are addressed with structured modules and multiple visits where budgets allow (Amuta, *et al.*, 2020, Ezeanochie, Akomolafe & Adeyemi, 2022, Filani, Olajide & Osho, 2020). Quality of administrative data is heterogeneous. Paper registries may contain duplicates, deceased beneficiaries, or “ghost” entries; deduplication uses probabilistic record linkage and community verification. E-voucher systems reduce some errors but introduce others SIM swaps, shared phones, and connectivity outages necessitating robust audit trails and fallbacks (offline tokens, one-time codes). Inventory records suffer from stock reconciliation issues and shrinkage; periodic physical counts and barcode/QR systems improve integrity. Payment records must be reconciled with procurement quantities to detect arrears; supplier claims include foreign exchange adjustments and demurrage, which should be separated to avoid inflating the subsidy unit cost attributed to farmer benefits (Giwah, *et al.*, 2020, Ibrahim, Amini-Philips & Eyinade, 2020).

Compliance measurement spans both program rules and agronomic recommendations. Program compliance includes eligibility verification, redemption within designated windows, and caps per hectare or per farmer; violation indicators feed leakage and targeting diagnostics. Agronomic compliance refers to application within recommended dose ranges, split timing, and balanced blends; this is captured through survey modules, extension records, and, in pilot settings, sensor-based monitors or smart applicators. Where feasible, simple soil test campaigns validate whether recommended blends match local needs; deviations inform both effectiveness and environmental risk (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019).

Constructing variables for environmental accounting requires careful proxies. Nitrogen surplus per hectare equals N applied (synthetic plus organic) minus N removed in harvested biomass and adjusted for biological fixation in legume rotations; this variable, combined with rainfall and soil texture, drives leaching and runoff scores. Emissions proxies convert N surplus to nitrous oxide using IPCC Tier 1/2 factors with country-specific adjustments when available. Water quality indicators use distance-to-watercourses, slope, and buffer vegetation as risk multipliers. These proxies are linked to subsidy intensity and timing to estimate marginal environmental effects of program designs.

Finally, integration and validation close the data loop. A reconciliation engine enforces mass and energy balance

consistency at the plot and farm levels where applicable (e.g., fertiliser in vs. nutrients removed), and budget consistency at the program level (procurement + logistics = redemptions + losses + inventory change). Outlier detection flags implausible values yields several standard deviations above local maxima, redemption volumes exceeding plausible land capacity and routes them for verification (Bankole & Tewogbade, 2019, Fasasi, *et al.*, 2019). Uncertainty is propagated from measurement error distributions into model inputs, yielding credible intervals for key performance metrics such as additional yield, cost-effectiveness, leakage rates, and poverty impacts. Sensitivity analysis identifies variables to prioritize in future data collection often delivery timing, effective price dispersion, soil quality, and beneficiary identification accuracy. With this scaffold, the analytical model rests on traceable, quality-controlled variables that credibly link subsidy design to productivity, welfare, fiscal, and environmental outcomes.

6. Model Specification and Identification

The analytical model for examining fertiliser subsidy performance and economic outcomes integrates structural and semi-structural relationships linking production decisions, input demand, price transmission, and welfare outcomes. The specification combines microeconomic behavioural equations with market and policy feedbacks, designed for estimation using household, market, and administrative panel data (Giwah, *et al.*, 2020, Ibrahim, Amini-Philips & Eynade, 2020).

At its core lies the production structure that defines how fertiliser and other inputs translate into output. A flexible functional form typically Cobb–Douglas or translog is adopted to allow diminishing marginal productivity and input substitution. For farm i in season t , output Y_{it} is specified as

$$\ln Y_{it} = \alpha_i + \beta_F \ln F_{it} + \beta_L \ln L_{it} + \beta_K \ln K_{it} + \beta_O \ln O_{it} + \epsilon_{it},$$

where F denotes fertiliser (subsidised + commercial), L labour, K capital, O other variable inputs, and α_i captures time-invariant farm heterogeneity (management skill, soil quality). The production elasticity of fertiliser, β_F , varies across farm size and agro-ecological zone by interacting fertiliser with categorical dummies or continuous moderators. Subsidy design enters through an effective price variable, $P_{fit}^{eff} = P_{fit}(1 - s_{it})$, where s_{it} is the subsidy rate; expected yield response then reflects how lower prices shift input intensities.

Input demand equations connect effective prices to fertiliser quantities. A semi-structural demand model specifies

$$\ln F_{it} = \gamma_0 + \gamma_1 \ln P_{fit}^{eff} + \gamma_2 \ln P_{yt} + \gamma_3 Z_{it} + \eta_i + \mu_t + v_{it},$$

where P_{yt} is the output price, Z_{it} vectors household characteristics (credit, education, extension, risk attitudes), and η_i, μ_t are farm and year fixed effects. Price elasticities (γ_1, γ_2) capture substitution and profitability channels, while cross-effects test complementarity between fertiliser and labour or irrigation. This structure allows decomposition of observed input changes into substitution effects (due to price) and scale effects (due to higher expected yield and profitability).

Market-level equations link micro behaviour to price pass-

through. Supply S_t and demand D_t for fertiliser define equilibrium domestic price P_{ft} . Supply depends on import costs P_{ft}^{int} exchange rate e_t , and government procurement decisions:

$$\ln P_{ft} = \delta_0 + \delta_1 \ln P_{ft}^{int} + \delta_2 e_t + \delta_3 Q_t^{gov} + u_t,$$

while demand aggregates farm-level consumption weighted by subsidy access. These structural links quantify how world price shocks and exchange-rate movements transmit into domestic markets under different subsidy regimes. For outputs, the farm-gate price P_{yt} follows a reduced-form pass-through model:

$$\Delta \ln P_{yt} = \phi_0 + \phi_1 \Delta \ln Y_t^{agg} + \phi_2 \Delta \ln M_t + \phi_3 \Delta \ln T_t + \xi_t,$$

where Y_t^{agg} is aggregate output, M_t imports, and T_t trade costs. This captures how increased yields from subsidies feed back into market prices and, by extension, welfare.

Identifying causal effects of fertiliser subsidies is complicated by non-random program placement, self-selection, and simultaneity between fertiliser use and yields. Several complementary identification strategies mitigate these biases. Instrumental variables (IV) exploit exogenous variation in effective fertiliser prices. Instruments include distance to the nearest distribution centre, timing of voucher release, administrative cut-off rules, or historical political alignment that affects allocation but not yield directly. In two-stage least squares (2SLS), the first stage predicts fertiliser use from instruments, and the second stage estimates the effect on output or income. The validity of these instruments is verified through over-identification tests and falsification checks on pre-program outcomes (Atobatele, Hungbo & Adeyemi, 2019).

Difference-in-differences (DiD) designs are feasible when panel or repeated cross-section data exist around program introductions or reforms. By comparing beneficiary and non-beneficiary farms before and after implementation, the model estimates average treatment effects conditional on parallel-trend assumptions:

$$Y_{it} = \theta_0 + \theta_1 (Treatment_i \times Post_t) + \theta_2 X_{it} + \eta_i + \mu_t + \epsilon_{it}.$$

Reforms such as transitions from universal to targeted vouchers or digital rollouts create quasi-experiments; staggered adoption allows event-study estimation of dynamic effects, testing persistence and lag structures. To strengthen identification, synthetic control methods can construct counterfactual regions or groups matching pre-reform trajectories in output, prices, and fertiliser use.

Regression discontinuity (RD) exploits explicit eligibility cut-offs for instance, landholding thresholds, registration scores, or e-wallet balances. If assignment near the threshold is as good as random, local average treatment effects can be estimated:

$$Y_i = \beta_0 + \beta_1 D_i + f(R_i - c) + \epsilon_i,$$

where $D_i = 1$ if the running variable R_i (e.g., farm size) exceeds cutoff c . Bandwidth selection and continuity tests ensure robustness. RD captures short-run causal effects for

marginally eligible farms, complementing broader DiD or IV estimates.

Panel fixed-effects (FE) models control for time-invariant unobserved heterogeneity soil quality, managerial skill, risk preferences that correlate with both subsidy uptake and outcomes. The FE estimator eliminates farm-specific means:

$$\tilde{Y}_{it} = \beta_1 \tilde{F}_{it} + \beta_2 \tilde{X}_{it} + \tilde{\epsilon}_{it},$$

where tildes denote deviations from within-farm averages. This approach leverages within-unit variation from changing subsidy access or price across years. Combined with year effects, it isolates short-term responses to policy changes, albeit assuming limited structural change in production technology.

Because each method has limitations, the model employs triangulation: FE for baseline robustness, IV for endogeneity correction, DiD for dynamic causal inference, and RD where eligibility thresholds exist. Bayesian hierarchical variants can pool information across identification contexts, generating posterior distributions for elasticity and treatment parameters that propagate uncertainty transparently (Eyinade, Amini-Philips & Ibrahim, 2020, Tewogbade & Bankole, 2020).

Heterogeneity across farms, genders, and regions is intrinsic to agricultural systems and must be modelled explicitly. The analytical framework introduces interaction terms or separate regimes to capture differential responses. Farm size is proxied by cultivated area or asset index; smallholders may face liquidity and risk constraints that attenuate price responsiveness, while larger farms can exploit economies of scale. The model allows

$$\beta_F = \beta_{F0} + \beta_{F1} Size_i + \beta_{F2} Size_i^2,$$

So marginal productivity varies along the size distribution. Quantile regression or heterogeneous treatment-effect models (e.g., random-coefficient or machine-learning-based causal forests) further expose distributional patterns identifying whether subsidies disproportionately benefit the top quantiles of land or asset holders.

Gender heterogeneity enters through interaction of treatment with female headship or intra-household decision roles. Because women often manage smaller plots and have weaker access to extension and credit, their price elasticities and yield responses differ. The model estimates separate coefficients or allows gender to modify both the fertiliser demand and yield response equations. These interactions inform whether gender-sensitive targeting improves aggregate and equity outcomes (Amini-Philips, Ibrahim & Eyinade, 2020, Essien, *et al.*, 2020).

Spatial heterogeneity is introduced through district fixed effects and agro-ecological dummies capturing rainfall regimes, soil fertility, and market access. Cross-level interactions between subsidy intensity and agro-climatic zones identify how environmental conditions mediate effectiveness. Incorporating geo-referenced weather and soil data allows semi-parametric estimation of non-linear yield responses to fertiliser under different moisture or fertility baselines. Spatial econometric extensions contiguity or distance-weighted spillover matrices detect whether fertiliser adoption or yield gains diffuse across neighbouring farms, illuminating local general-equilibrium effects.

Crop-system heterogeneity is also critical. Input responsiveness varies among cereals, legumes, tubers, and

horticultural crops; nutrient ratios and timing differ by phenology. The model stratifies by crop or estimates a system with crop-type fixed effects, ensuring subsidy impacts are not conflated across agronomic contexts. Multi-output translog systems allow cross-price effects among crops competing for land and inputs, revealing whether subsidies crowd land away from legumes or export crops (Bankole, Nwokediegwu & Okiye, 2020, Obuse, *et al.*, 2020). This multi-crop specification captures opportunity costs and biodiversity implications often missed in single-crop analyses.

For policy simulation, estimated elasticities and structural coefficients feed into a calibrated multi-equation system linking input demand, production, and prices to fiscal cost and welfare. Dynamic simulations propagate shocks changes in subsidy rates, targeting accuracy, world prices, or rainfall through the equations, producing trajectories for yields, incomes, leakage, and budget balances. Sensitivity analysis quantifies uncertainty from parameter estimates and identification choices, while counterfactuals illustrate the marginal value of reforms such as digital targeting or rate adjustments (Aduwo & Nwachukwu, 2019, Erigha, *et al.*, 2019).

Overall, the model specification integrates structural realism with econometric identification, balancing theory-driven equations and empirically grounded estimation strategies. Its architecture acknowledges that fertiliser subsidies operate through simultaneous markets, behavioural responses, and heterogeneous conditions; therefore, identification must exploit multiple quasi-experimental designs and diverse data panels to uncover causal and distributional truths rather than average correlations. By uniting these elements production and demand functions, pass-through equations, rigorous identification, and explicit heterogeneity the analytical model provides a transparent, policy-relevant instrument for understanding when and how fertiliser subsidies enhance productivity, improve welfare, and remain fiscally and environmentally sustainable (Fasasi, *et al.*, 2020, Giwah, *et al.*, 2020).

7. Evaluation Strategy and Metrics

The evaluation strategy for an analytical model that examines fertiliser subsidy performance and economic outcomes must be both comprehensive and multidimensional, integrating metrics that reflect efficiency, equity, fiscal sustainability, productivity, welfare, environmental stewardship, and cost-effectiveness. Fertiliser subsidies operate through complex channels that influence farmer behaviour, market equilibria, government budgets, and ecological processes; thus, a single indicator cannot capture overall success or failure. The framework therefore adopts a systems evaluation logic, where performance indicators are organized around three interlinked domains economic efficiency and welfare, fiscal sustainability, and environmental externalities underpinned by rigorous benefit–cost and sensitivity analysis to judge the robustness of results across policy and scenario variations (Akinrinoye, *et al.*, 2020, Alao, Nwokocha & Filani, 2020). Efficiency measures form the cornerstone of performance assessment. Technical efficiency evaluates how effectively fertiliser translates into yield gains relative to agronomic potential. Using estimated production functions, technical efficiency scores are computed for each farm as the ratio of observed to frontier output, conditional on input use and agro-ecological conditions. Aggregating these scores reveals whether subsidies move the efficiency frontier outward by

accelerating technology diffusion or merely shift resources among producers. Allocative efficiency assesses whether input use proportions approach cost-minimizing combinations given prevailing prices, indicating whether subsidy-induced price distortions push farmers toward over-application or balanced nutrient use (Akintayo, *et al.*, 2020, Dako, *et al.*, 2020). Dynamic efficiency extends this analysis over time, measuring productivity growth (e.g., total factor productivity) and the degree to which subsidies foster sustained improvements versus transient boosts.

Equity indicators gauge the inclusiveness of program benefits. These include targeting accuracy the share of subsidised fertiliser reaching intended groups such as smallholders or women farmers and benefit incidence, calculated from concentration indices comparing subsidy receipts with income or landholding distributions. A perfectly equitable program would show a progressive distribution where poorer quintiles capture a larger share of benefits relative to their baseline income share. Gender equity metrics measure women's access to subsidised inputs, extension services, and decision power over application. Geographic equity assesses whether regions with lower baseline yields or higher poverty receive proportionally greater support. Together, these metrics illuminate whether subsidies reduce or reinforce existing inequalities (Atobatele, *et al.*, 2019, Filani, Nwokocha & Babatunde, 2019).

Fiscal sustainability links efficiency and equity to macroeconomic viability. Indicators include fiscal cost as a percentage of agricultural GDP, cost per beneficiary, and arrears accumulation. A dynamic fiscal projection module tracks how program expenditures evolve with world fertiliser prices, exchange-rate movements, and delivery efficiency. Fiscal risk exposure the variance of program cost under plausible shocks is quantified using Monte Carlo simulations, while the fiscal multiplier measures the ratio of value added or poverty reduction to public expenditure. Programs exhibiting high multipliers and low variance are deemed fiscally resilient. The model also evaluates crowding out of other agricultural investments: if rising subsidy budgets reduce allocations to research, irrigation, or roads, the long-term fiscal efficiency declines even when short-term productivity appears strong (Bankole, *et al.*, 2019, Nwokediegwu, Bankole & Okiye, 2019).

Economic outcomes encompass yield, income, poverty, prices, and trade balance, translating intermediate agronomic responses into welfare and macro indicators. Yield metrics are computed as percentage change in output per hectare relative to baseline and decomposed into area expansion, intensity, and technology effects. These yield effects, aggregated regionally, generate changes in total agricultural output, which in turn influence rural incomes. Farm income measures incorporate revenues minus variable input costs, while household income extends to non-farm earnings and transfers to capture general equilibrium feedbacks. Poverty impacts are evaluated using standard headcount, gap, and severity indices, with counterfactual income distributions constructed through microsimulation. If survey data allow, stochastic dominance tests determine whether welfare improvements hold across poverty lines, avoiding arbitrary thresholds (Ajayi, Onunka & Azah, 2020, Obuse, *et al.*, 2020).

Price and market effects are critical to contextualize welfare changes. Increased production can reduce farm-gate prices; hence, price elasticity of supply and demand determines net

income effects. The model simulates market-clearing prices under different output and import conditions, capturing pass-through to consumers and traders. Consumer price indices for staple foods quantify subsidy-induced food price moderation, while producer price indices assess farm profitability. For open economies, trade balance indicators measure changes in fertiliser imports, crop exports, and foreign exchange savings (Patrick, *et al.*, 2019). A positive trade balance improvement occurs when higher domestic production reduces import dependency without offsetting increases in fertiliser imports; conversely, sharp import bill growth due to rising fertiliser prices or exchange-rate depreciation signals external vulnerability.

Environmental metrics complete the performance profile, internalizing costs often excluded from economic analysis. The central indicator is nutrient surplus, calculated as nutrient inputs (synthetic fertiliser, manure, biological fixation) minus outputs removed in harvest, adjusted for storage and volatilization losses. Positive surplus values indicate potential nutrient buildup and risk of leaching or runoff. Runoff intensity translates these surpluses into hydrological risk using rainfall, soil permeability, and slope coefficients; higher scores imply greater water pollution potential. Soil health metrics monitor changes in organic matter, pH, and cation exchange capacity, providing a long-term view of sustainability (Fasasi, *et al.*, 2020, Giwah, *et al.*, 2020, Hungbo, Adeyemi & Ajayi, 2020). Where data permit, indicators of soil nutrient balance (N:P:K ratios) measure whether subsidies promote balanced fertilisation or excessive nitrogen bias, which degrades soil structure and microbial activity.

The framework also captures air and water externalities through emission factors linking nutrient surpluses to greenhouse gas emissions chiefly nitrous oxide expressed as CO₂-equivalent per hectare. Cumulative nutrient surplus and emission indicators are integrated into an environmental damage cost function, monetizing losses in water quality, biodiversity, and climate regulation. This allows direct comparison of environmental costs with productivity gains in benefit–cost analysis. Programs that achieve high yield and income gains but impose large external costs may appear beneficial in the short term yet prove inefficient once environmental degradation is valued (Awe, Akpan & Adekoya, 2017, Osabuohien, 2017).

Evaluating cost-effectiveness requires combining these economic and environmental dimensions. The primary ratio, cost per incremental tonne of output, divides net fiscal expenditure by additional production relative to baseline. Complementary metrics include cost per percentage point reduction in poverty and cost per additional dollar of farm income. These are benchmarked against alternative interventions such as cash transfers, extension, or irrigation to assess relative efficiency. Benefit–cost analysis (BCA) integrates all monetized benefits (yield gains, consumer price reductions, trade savings) and costs (subsidy outlays, administrative expenses, environmental damages) into a single measure:

$$BCR = \frac{\sum_t \frac{B_t}{(1+r)^t}}{\sum_t \frac{C_t}{(1+r)^t}}$$

where B_t and C_t are annual benefits and costs and r is the social discount rate. A benefit–cost ratio (BCR) greater than

one indicates net social gain. Sensitivity analysis varies r , yield elasticities, and damage coefficients to test robustness. Net present value (NPV) and internal rate of return (IRR) further translate long-term benefits into investment metrics suitable for budgetary comparison with competing programs (Akpan, Awe & Idowu, 2019, Ogundipe, *et al.*, 2019).

Beyond averages, the model's evaluation strategy emphasizes uncertainty and distributional impacts. Stochastic dominance and probability-weighted welfare curves show the likelihood that the subsidy delivers positive outcomes across income groups. Monte Carlo simulations propagate uncertainty from input data (yields, prices, fiscal costs) through to outputs, yielding confidence intervals for key metrics such as cost-effectiveness or nutrient surplus. Scenario analysis explores alternative futures climate shocks, global price spikes, policy reforms (e-voucher adoption, rate adjustments) revealing how resilient program performance remains under stress (Awe & Akpan, 2017).

Dynamic evaluation ensures sustainability over time. Indicators track whether yield and income gains persist after subsidy withdrawal or tapering, distinguishing between temporary and structural effects. A sustainability index combines persistence of productivity gains, fiscal stability, and environmental trends; programs scoring high demonstrate learning and self-sustaining adoption, while low scores indicate dependency. Linkage to national accounts and climate reporting frameworks ensures coherence with broader development objectives such as SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

To integrate multi-dimensional metrics into policy dashboards, the model employs composite scoring. Each performance domain efficiency, equity, fiscal, environmental is normalized and weighted according to stakeholder priorities. The resulting composite index facilitates cross-country or cross-period comparisons and enables ranking of alternative subsidy designs. Decision-makers can visualize trade-offs, for instance, between higher yield efficiency and greater fiscal risk, or between rapid poverty reduction and increased nutrient surplus (Akpan, *et al.*, 2017, Oni, *et al.*, 2018).

In sum, the evaluation strategy for the analytical model is both quantitative and systemic. It extends beyond yield response to encompass who benefits, at what cost, under what fiscal and environmental constraints. Efficiency indicators ensure resources translate into real productivity; equity metrics safeguard inclusiveness; fiscal and environmental dimensions secure long-term viability. By embedding benefit-cost analysis within this multidimensional framework, policymakers can discern whether fertiliser subsidies deliver genuine social returns or require redesign. The model's ultimate value lies in its capacity to inform adaptive management using continuous performance feedback to recalibrate subsidy rates, targeting mechanisms, and complementary investments ensuring that agricultural growth, fiscal prudence, and environmental stewardship advance together.

8. Scenario, Sensitivity, and Robustness Analysis

Scenario, sensitivity, and robustness analysis provide the stress-testing spine of the analytical model, turning point estimates into decision guidance that is credible under uncertainty and transferable across contexts. The scenario layer begins with policy design levers targeting rules, rate

schedules, and delivery channels because design choices shape who receives subsidised fertiliser, when, at what effective price, and with what behavioural response. Targeting rules are parameterised from narrow (quota per hectare for registered smallholders, with geofenced redemption) to broad (universal price cuts at public outlets). Intermediate variants include poverty or farm-size thresholds, female-headed household prioritisation, soil-test eligibility, and performance conditions (e.g., micro-dosing training) (Akomea-Agyin & Asante, 2019, Awe, 2017, Osabuohien, 2019). For each rule, the model programs beneficiary shares by income quintile, gender, and agro-ecology, and computes implied additionality and leakage. Rate schedules are tested as fixed ad valorem discounts (e.g., 30% off shelf price), floating rates tied to import parity (maintain a target effective price band), and declining schedules that taper over seasons to encourage learning. Delivery channels span paper coupons via cooperatives, e-vouchers redeemable at private dealers, and direct input transfers through public warehouses; hybrid channels blend private last-mile with public procurement. The model encodes how each channel alters timeliness, stock-out probabilities, crowding out of private dealers, and transaction costs borne by farmers, then propagates these into yield, welfare, and fiscal outcomes.

Shock scenarios inject realism. Price spikes are simulated as stochastic jumps in world fertiliser prices and exchange rates, drawing from historical volatility with fat tails. The model adjusts procurement costs, domestic supply, and arrears risk; floating rate rules reduce fiscal variance but increase on-farm price variance, while fixed discounts stabilise farmer prices at the cost of wider fiscal swings. Rainfall variability is introduced through seasonal rainfall distributions, onset/cessation shifts, and drought probabilities mapped to plots. Yield response functions become conditional on water, so late delivery during poor rains has a larger negative marginal product. Supply bottlenecks cover port congestion, trucking constraints, and payment delays; they propagate as delivery lags, stock-outs, and effective price dispersion across space (Asata, Nyangoma & Okolo, 2020, Bukhari, *et al.*, 2020, Essien, *et al.*, 2020). Each shock is run singly and in combination (e.g., global price spike plus currency depreciation plus port congestion), because real crises cluster. The outputs yield distributions, income and poverty trajectories, header fiscal costs, and nutrient surpluses are reported as fan charts with percentile bands so decision-makers see both central tendencies and tail risks.

Sensitivity analysis explores the model's dependence on structural parameters. Key elasticities include fertiliser demand with respect to effective price, yield response to kilograms applied under varying soils and moisture, and price pass-through from aggregate output to farm-gate prices. Because literature values vary, the model samples these from credible priors and re-estimates outcomes. If policy rankings flip when elasticities move within plausible ranges, conclusions are tagged as fragile. Leakage rates diversion at warehousing, reseller arbitrage, cross-border smuggling, and elite capture are similarly uncertain. The model varies system-level leakage from 5% to 35% and household-level resale propensities by distance to borders and price gaps, then recomputes cost-effectiveness and equity (Abass, Balogun & Didi, 2020, Amatere & Ojo, 2020, Imediegwu & Elebe, 2020). Compliance assumptions application timing, balanced blends, and adherence to per-hectare caps are relaxed to

reflect real behaviour; higher non-compliance reduces agronomic response and increases nutrient surplus, revealing how much of the program's benefit hinges on extension and monitoring quality. Crucially, the model conducts one-at-a-time and global (Sobol/variance-based) sensitivity, identifying which parameters drive most of the variance in NPV, poverty reduction, and environmental damages. This ranking guides data collection and institutional focus: if delivery timeliness elasticity dominates outcomes, investment in logistics and voucher release discipline yields larger returns than marginally changing the nominal rate.

Robustness is judged by performance under regret and risk criteria, not by average outcomes alone. For each design, the model computes the maximum regret relative to the best design across shocks, the conditional value at risk (tail loss) for fiscal costs, and the probability of breaching constraints (e.g., poverty reduction below a threshold, nutrient surplus above a watershed cap). Designs that minimise worst-case regret and tail fiscal risk while keeping environmental breaches rare are flagged as robust (Adesanya, *et al.*, 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020). Example results often show that targeted e-vouchers with floating rates and explicit quantity caps produce slightly lower mean yield gains than universal price cuts in benign years but dramatically lower fiscal losses and leakage under price spikes, preserving poverty impacts within acceptable ranges. Likewise, coupling subsidies with soil testing and micro-dosing training may yield similar average production but reduces nutrient surplus variance, a critical robustness dimension for environmental regulators.

Scenario analysis also addresses temporal robustness. The model simulates multi-season trajectories with adaptive expectations: if implementation is timely and reliable, farmers revise upward their belief in on-time supply, increasing optimal application and improving yields; if delays persist, they discount future participation, raising resale and reducing additionality. Designs that maintain high on-time delivery even at modest subsidy rates tend to dominate in the medium term because credibility compounds. The framework quantifies this by comparing three- to five-year cumulative outcomes, showing that tapering schedules paired with strong delivery and extension can maintain productivity gains while gradually lowering fiscal exposure (Akinrinoye, *et al.* 2015, Bukhari, *et al.*, 2019, Erigha, *et al.*, 2019).

External validity and scalability are assessed by transporting the model to new settings and scaling interventions up within a country. External validity begins with out-of-sample prediction: parameters estimated in pilot regions are used to predict outcomes in holdout regions differing in soils, market access, and governance. Prediction errors are analysed for systematic bias e.g., underperformance in high rainfall zones due to unmodelled leaching triggering model refinement (additional soil-rainfall interactions) or caution in extrapolation. Cross-country portability is addressed through modular calibration: agronomic response functions, market pass-through, and fiscal procurement modules are re-parameterised with country-specific data while preserving structural form. The model documents data pedigree and warns when critical inputs (e.g., leakage audits or soil maps) are missing, preventing overconfident conclusions.

Scalability within a country is tested for general-equilibrium and capacity constraints that pilots rarely hit. As coverage expands, private dealer incentives, warehouse throughput,

and road congestion change; the model embeds capacity constraints and increasing marginal logistics costs, revealing at what scale crowding out of private retail becomes material and when port or trucking bottlenecks dominate timeliness. Fiscal scalability is tested against medium-term expenditure frameworks: stochastic price paths project the distribution of budget shares under different coverage levels, highlighting thresholds where subsidies cannibalise complementary investments (extension, irrigation) that are critical for sustained gains. Environmental scalability is examined by aggregating nutrient surplus across watersheds; a design safe at pilot scale may breach basin caps when scaled, motivating regional differentiation or conditional caps.

A critical robustness check contrasts policy ranking under alternative social objective weights. If planners prioritise poverty reduction, the composite metric weights equity and consumption smoothing more heavily; if macro stability dominates, fiscal risk enters with higher weight; if water quality is binding, nutrient surplus constraints become hard. The model recomputes Pareto sets for these alternative weightings and reports how rankings shift. A design that remains near the Pareto "knee" across weightings is practically robust across political cycles and stakeholder preferences. Similarly, discount rate sensitivity is evaluated: higher social discounting penalises programs with delayed benefits (learning and soil buildup) versus immediate output; programs that survive plausible discount ranges are less prone to policy reversals.

To guard against model structural error, the robustness suite includes adversarial tests. First, partially blank out modules (e.g., assume no pass-through to output prices, or no leakage) and observe how much the optimal design changes; heavy dependence on a single contested mechanism indicates fragility. Second, replace structural components with alternative plausible forms translog versus Cobb–Douglas production, linear versus nonlinear pass-through and re-optimize. Third, scramble shock correlations (e.g., make droughts coincide with price spikes) to test tail co-movements. Where rankings are sensitive, policy guidance is framed conditionally and paired with monitoring triggers to update choices as evidence accumulates.

Finally, the analysis is operationalised into decision playbooks. For each design lever set, the model produces a two-page brief with central KPIs, tail risks, and "red lines" (budget breach probabilities, watershed surplus caps, minimum on-time delivery thresholds). It also lists leading indicators voucher redemption delays, private dealer exits, border price gaps that, if breached, signal heightened risk and trigger contingency moves (tighten caps, slow rollout, shift to cash transfers). This turns robustness from a static appendix into a living governance protocol.

In sum, scenario, sensitivity, and robustness analysis transform the analytical model from an academic exercise into a policy instrument that remains reliable when reality diverges from plan. By systematically varying design levers, injecting realistic shocks, probing parameter uncertainty, and testing external validity and scalability, the framework elevates recommendations that are not just optimal on average but resilient, fiscally prudent, and environmentally defensible under the messy conditions policymakers actually face.

9. Conclusion

This paper developed an analytical model that links farm

behavior, market transmission, fiscal accounts, and environmental externalities to evaluate fertiliser subsidies in a way that is causal, comparative, and operational. By nesting a farmer decision system with risk and liquidity constraints inside market pass-through and trade modules, and by closing the loop through a government budget–environment block, the framework translates design levers targeting, rate schedules, and delivery channels into trajectories for yields, incomes, poverty, prices, fiscal exposure, and nutrient surpluses. The synthesis across sections yields four consistent findings. First, the effectiveness of subsidies hinges more on implementation quality timeliness, targeting accuracy, and crowding-out avoidance than on nominal rates. Second, equity and efficiency are not in inherent conflict: when vouchers are digitally targeted, time-bound, and paired with agronomic guidance, smaller and women-managed farms exhibit larger marginal gains per public dollar than universal price cuts. Third, fiscal resilience is the decisive constraint under global price and exchange-rate shocks; floating rate rules with explicit quantity caps and contingency triggers stabilize budgets with limited loss of average productivity. Fourth, environmental outcomes are design variables, not exogenous costs: bundling soil testing, balanced blends, and micro-dosing training can hold nutrient surplus and runoff intensity flat or reduce them even as yields rise. These gains are possible because the model converts diffuse evidence into calibrated, scenario-tested choices that respect agronomy, markets, budgets, and watersheds simultaneously.

Limitations qualify these conclusions. Data gaps especially in delivery timing, leakage audits, soil quality, and high-frequency prices can widen uncertainty bands and shift policy rankings. Identification strategies (IV, DiD, RD, FE) mitigate endogeneity but cannot purge all selection and implementation bias, particularly where programs co-move with political cycles. Agronomic response and pass-through equations, while flexible, remain approximations that may miss rare nonlinearities in extreme weather or during systemwide supply bottlenecks. Environmental accounting often relies on Tier 1/2 emission factors and nutrient proxies rather than direct measurements; watershed heterogeneity and legacy soil dynamics introduce error that only richer monitoring can shrink. Finally, scalability can expose capacity constraints port congestion, dealer exit, extension bandwidth that pilots underestimate. The model therefore emphasizes uncertainty propagation, robustness criteria (regret, tail risk), and explicit “red lines” to avoid overconfidence.

The policy implications are pragmatic and immediate: move from rate-centric, politically timed expansions to performance-based, data-driven redesign. Concretely, define program success with a compact dashboard incremental yield per kg subsidised, cost per tonne added, poverty reduction per public dollar, leakage rate, on-time delivery share, and nutrient surplus per hectare reported with confidence intervals and tracked weekly during seasons. Replace universal price cuts with digital e-vouchers targeted to verified smallholders (and women farmers where feasible), bounded by per-hectare caps and geofenced redemption at accredited private dealers to preserve market development. Adopt floating rate schedules that keep the farmer’s effective price within a band while hard-capping fiscal exposure via quantity limits and automatic de-escalators when world prices spike. Pair vouchers with light-touch conditionalities soil testing where labs exist, or mobile agronomy nudges on

timing and split application so that marginal kilograms deliver balanced nutrients with lower leakage into water and air. Write these design choices into transparent rules, published calendars, and grievance mechanisms to strengthen credibility and reduce strategic behavior.

A practical roadmap follows three phases: readiness, rollout, and adaptive operations. In readiness, establish the data backbone and governance: clean the beneficiary registry (deduplicate and verify with community audits), integrate voucher, redemption, procurement, and payment systems with time stamps, and deploy minimal metering at warehouses and sample dealers. Stand up a reconciliation engine that closes quantities and cash every week and a public dashboard that publishes KPIs. Build the model’s country calibration using recent farm surveys, admin records, and gridded weather and soils; estimate elasticities and leakage baselines; and run pre-implementation scenarios to set initial caps, bands, and contingency triggers.

In rollout, start with a limited set of districts representing distinct agro-ecologies. Use accredited private dealers as the default last-mile channel, with public outlets as backstops where retail networks are thin. Sequence distribution to hit agronomic windows (basal first, then topdressing), and publish delivery calendars. Pilot soil-test-informed blends where labs exist; elsewhere, deliver standard balanced NPK and embed micro-dosing tips by SMS/IVR. Execute a measurement and verification plan: independent spot checks on delivery timeliness, covert shopper price audits to estimate effective prices and crowding out, crop-cut campaigns on sentinel plots, and quarterly leakage audits using inventory reconciliation and anomaly detection.

In adaptive operations, treat the program as a controllable system. Each week, feed new data into the digital twin to update posteriors on elasticities and leakage; recompute fiscal exposure under current world prices and exchange rates; and evaluate whether KPIs track plan with bands. If on-time delivery slips or leakage rises above thresholds, tighten quantity caps, shift stock to better-performing dealers, or pause redemptions in hot-spot border districts. If rains fail, pivot budget from topdressing vouchers toward drought support or cash transfers. If fiscal risk breaches VaR limits, trigger automatic rate de-escalation and extend caps. Publish these rules *ex ante* so adjustments are mechanical, not political. After each season, run a full *ex-post* evaluation (DiD/event study) and update parameters, caps, and bands for the next cycle.

Priorities for future research align with the model’s bottlenecks. First, digital targeting needs rigorous A/B testing around inclusion and exclusion errors, privacy safeguards, and resilience to SIM sharing or weak connectivity. Interoperable, privacy-preserving linkages between registries, voucher logs, and dealer POS data can cut leakage while enabling real-time equity analytics; research should evaluate human-centered designs that keep access simple for smallholders, especially women. Second, environmental safeguards require better measurement: cost-effective soil testing at scale (spectroscopy, citizen science kits), watershed-level nutrient and flow monitoring, and locally calibrated emission factors to replace coarse proxies. Third, agronomic and behavioral heterogeneity calls for adaptive policies: contextual bandits or Bayesian updating in rate and cap setting can learn which mixes of conditionalities and messaging deliver the best yield-to-surplus ratios by zone and group. Fourth, market development effects deserve long-

horizon study: how do different delivery channels reshape dealer density, credit provision, and input innovation, and what transition paths minimize crowding out? Finally, macro-fiscal integration should explore contingent financing and risk-sharing catastrophe clauses with suppliers, price hedging, and stabilization funds so that productivity support survives global shocks without cannibalizing core public goods.

In closing, the central message is less about a single “best” subsidy and more about a disciplined way to choose, operate, and evolve support. A performance-based, data-driven redesign anchored in transparent rules, real-time monitoring, and explicit environmental guardrails can convert fertiliser spending from a recurrent fiscal liability into a targeted instrument for productivity, equity, and resilience. The analytical model provides the scaffold; durable value will come from the institutions that use it to learn, adjust, and stay honest about trade-offs as conditions change.

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