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Brill-Viz

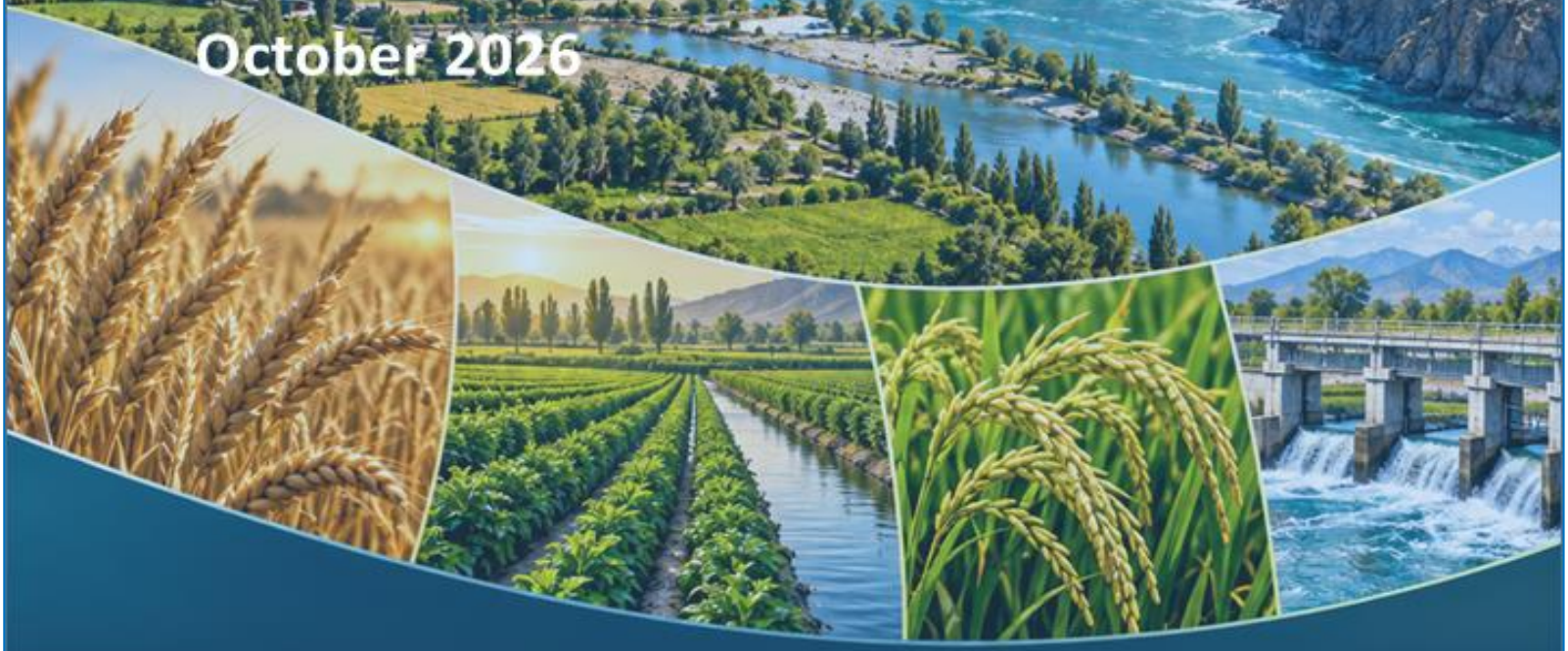
Water, Agriculture & Food Security in Pakistan



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Water Resources & Irrigation • Agricultural Productivity
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Abstract

Pakistan's food security depends not only on the volume of agricultural production but on how effectively scarce water, land, capital, energy and technology are converted into stable food supply, economic value and retained post-harvest output. This synthesis evaluates those relationships over 2000-2025 using a harmonized national macro-climate series, a formal 2007-2024 crop panel, international water/agriculture comparators, trade and real-price evidence, provincial WASH data, demographic and rainfall benchmarks, crop genetics/biotechnology evidence, and a near-global demographic-macro-financial-energy context layer. The completed historical economics and econometrics layer shows broad positive yield trends across the six harmonized crops, a marked rise in edible-oil import exposure, and a much faster increase in the nominal import bill than in physical import quantity. Total edible-oil imports increased from about 1.70 million tonnes in 2005-06 to 3.14 million tonnes in 2023-24, while the nominal bill increased from about PKR 44.2 billion to PKR 831.7 billion; the symmetric accounting bridge attributes about 26.7% of that nominal increase to quantity change and about 73.3% to unit-value change. Representative farm-economics screening for banana, maize, potato, rice, sugarcane and wheat has also been completed in Brill-Viz, but these cases use regional/proxy price, cost, water and loss evidence and are not nationally representative farm-profitability estimates.

The farm screening results are deliberately heterogeneous: maize and potato are positive under the stated assumptions; rice is approximately at break-even; sugarcane is only marginally positive; wheat is slightly below break-even; and banana is substantially negative. These contrasts reinforce a central finding of the synthesis: biological yield improvement does not automatically translate into farm profitability because output price, production cost, post-harvest loss and water requirement jointly determine economic performance. Preservation and irrigation screening likewise remains conditional. AG01 wheat storage is positive under its illustrative assumptions (NPV about US$221.5 thousand; IRR 24.4%), whereas AG02 rice drying (NPV about -US$103.6 thousand; IRR 7.2%) and AG03 canal/water-recovery screening (NPV about -US$74.3 thousand; IRR 9.1%) do not clear the 12% base discount rate. These are internally calculated, assumption-dependent screening cases, not realized Pakistan project outcomes. Advanced WaPOR crop-water productivity, nationally representative farm-cost/profitability data, verified full-life preservation and irrigation project economics, spatial econometrics and final scenario calibration remain principal evidence gaps.

Scope and evidence statement. *Historical source observations, accounting identities, statistical estimates, and illustrative farm/project cases have different evidentiary standing. Checks of formulas and consistency can identify arithmetic errors; they cannot verify unobserved field costs, physical water recoveries, realized losses or commercially achieved returns. The study therefore offers an integrated, qualified baseline for policy discussion and research prioritization, not nationally representative farm-income estimates, causally identified policy effects, bankable asset valuations or empirically calibrated 2030-2050 forecasts.*

Key Take-Aways

The synthesis points to an integrated water-agriculture-food challenge rather than a single production deficit. The main take-aways are:

- **Agricultural productivity has improved, but unevenly.** All six harmonized crop-yield series show positive historical trends. Maize and banana exhibit the largest relative gains, while wheat and rice improve more gradually. Yield growth alone, however, is not a sufficient measure of food-system performance.
- **Water productivity is the central resource constraint.** Pakistan combines a very large irrigation system with severe comparative water stress and relatively low whole-economy water productivity. Policy assessment therefore needs to move from infrastructure scale and total withdrawals toward crop output, economic value and resilience per unit of water.

- **Farm economics are heterogeneous and conditional.** The representative 100-ha screening cases do not support a single profitability narrative: maize and potato are strongly positive under the current assumptions; rice is approximately at break-even; sugarcane is only marginally positive; wheat is slightly below break-even; and banana is strongly negative. These are screening cases using regional/proxy inputs, not nationally representative farm-profitability estimates.
- **Post-harvest retention can create food without proportional land or water expansion.** Avoided losses preserve food, embedded water, energy and capital already invested in production. The economics nevertheless depend on commodity, utilization, energy cost, scale, market access and the actual reduction in loss.
- **Investment viability cannot be generalized from technology labels.** The three investment screening cases give different outcomes: AG01 wheat storage is positive under its illustrative assumptions (NPV about US$221.5 thousand; IRR 24.4%), while AG02 rice drying and AG03 irrigation recovery do not clear the 12% hurdle in their base cases. Project-specific CAPEX, OPEX, throughput, loss reduction and water-value evidence are required before investment decisions.
- **Food-import exposure is a major economic-security issue.** Edible-oil import quantity rose from about 1.70 million tonnes in 2005-06 to 3.14 million tonnes in 2023-24, while the nominal bill rose from about PKR 44.2 billion to PKR 831.7 billion. The accounting decomposition associates about 26.7% of the increase with quantity and 73.3% with nominal unit-value change (unit-value changes expressed in current rupees, without inflation adjustment); this is an accounting decomposition, not causal attribution.
- **Nominal food-price pressure must be separated from real price change.** The wheat wholesale series rises by about 10% per year in nominal terms, whereas the available inflation-adjusted price series shows no statistically significant long-run trend. Inflation, exchange rates and price definitions therefore matter when interpreting affordability and farm incentives.
- **Population and macro-financial capacity are part of food security.** Population has grown by about 2% per year over the 2000-2025 period, increasing the scale of future food, water and employment demand. Current-dollar GDP growth provides financing context but is not equivalent to real welfare growth, while energy and import exposure can transmit external shocks through irrigation, fertilizer, transport, storage and processing.
- **Spatial averages conceal important differences.** Irrigation source, groundwater dependence, rainfall, crop productivity and WASH conditions vary across Pakistan. GIS and remote sensing therefore needs to be used to target interventions rather than applying a uniform national prescription.
- **The policy implication is a portfolio, not a single intervention.** The evidence favors coordinated improvement in water productivity, crop and farm economics, storage and loss reduction, trade resilience, technology and breeding, WASH, data quality and scenario-based investment planning.
- **Evidence quality limits the strength of economic claims.** The six-crop and three-project evaluations are sensitivity-oriented screens, not field-verified estimates. A positive modeled NPV or margin is an assumption-conditional outcome rather than proof of a viable Pakistan investment. Residual autocorrelation, variable provenance and incomplete chart-level verification likewise constrain causal and comparative interpretations.

Economics evidence guardrail. Farm and project economics in this synthesis are indicative screening analyses unless complete, matched real-world data are available for the same crop/project, location and period. Full representative economics would require observed farm-gate prices, input quantities and costs, labour and land costs, measured water use, taxes/subsidies, financing, replacement capital, utilization, maintenance, residual values and uncertainty distributions. The current results support comparison, sensitivity analysis and research prioritization; they do not constitute investment advice or national profitability estimates.

Contents

Abstract 2
Key Take-Aways 2
Contents 4
1. Introduction and Research Rationale 7
1.1 Why the Water-Agriculture-Food Nexus Requires an Integrated Study 7
1.2 The 2000-2025 Perspective 7
1.3 From Production to Preservation and Value 7
1.4 Demographic Demand, Economic Capacity and Energy Exposure 8
2. Aims, Objectives and Research Questions 8
2.1 Overall Aim 8
2.2 Specific Objectives 8
2.3 Research Questions 9
3. Conceptual Framework 10
4. Data Architecture, Sources and Provenance 11
4.1 Core Analytical Structure 11
4.2 Provenance and Reproducibility Requirements 13
4.3 Consolidated Analytical Dataset and Harmonization Protocol 13
5. Literature Synthesis and Knowledge Gaps 13
5.1 Water Productivity Rather than Infrastructure Scale 13
5.2 Food Security as Availability, Access, Utilization and Stability 13
5.3 Post-Harvest Loss and Value-Chain Constraints 13
5.4 Food Trade and External Vulnerability 14
5.5 Demographic Transition, Food Demand and the Agricultural Workforce 14
5.6 Energy and Macro-Financial Exposure as Food-System Multipliers 14
5.7 Crop Genetic Improvement, Biotechnology and Advanced Breeding 14
5.8 Knowledge Gap Addressed by This Thesis 14
6. GIS and Remote-Sensing Framework 15
6.1 Spatial Role in the Thesis 15
6.2 Temporal Spatial Analysis 15
6.3 Spatial Integration Across the Research Chapters 15
6.4 Spatial-Data Integration and Reusable Outputs 16
6.5 Interpretation Across Spatial Scales 16
7. Pakistan Water Resources, Irrigation and Groundwater Context 16
7.1 The Indus Basin as the Production Backbone 16
7.2 Surface Water, Groundwater and Conjunctive Use 18

7.3 Irrigation Efficiency and Economic Productivity 19
7.4 Climate and Hydrological Risk 20
7.5 Current Quantitative Water and Climate Evidence 25
8. Agricultural and Food-Production System 28
8.1 Commodity Canvas 28
8.2 Production Quantity versus Nutritional and Economic Contribution 28
8.3 Major-Crop Production and Yield Results, 2007-2024 29
8.4 Crop Genetic Improvement, Biotechnology and Advanced Breeding 34
8.5 Representative Crop/farm Economics Screening 36
8.6 Economics Interpretation, Decision Thresholds and Underlying Chart Evidence 37
9. Food Trade, External Balance and Economic Security 39
9.1 Current Trade and Real-Price Evidence 39
9.2 Economic Transmission from Production to Food Security 41
9.3 Observed Agricultural-Trade Economics Completed for This Synthesis 43
10. Food Technology, Post-Harvest Science, Preservation, Storage and Value Retention 43
10.1 Why Food Technology and Preservation Belong Inside Food Security 43
10.2 Deterioration Mechanisms and Control Variables 43
10.3 Edible Coatings and Films as a Specific Horticultural Module 45
10.4 Cold Chain, Packaging and Emerging Food Technologies 45
10.5 Shelf Life, Expiry and Safety 46
10.6 Pakistan Alignment with International Post-Harvest Practice 47
10.7 Preservation Economics and Embedded-Resource Value 47
10.8 Analytical Programme and Evidence Readiness 49
10.9 Quantitative Post-Harvest Results Now Available 50
10.10 Full-Life and Point-Forward Investment Evidence and Sensitivities 54
11. WASH and Domestic Water-Security Context 56
11.1 Current Provincial WASH Evidence 56
12. Comparator-Country Rationale 60
12.1 Demographic and Rainfall Context for Comparator Interpretation 60
12.2 Demographic Transition, Economic Capacity and Food-System Demand 63
12.3 Integrated Performance Comparison: Water, Agriculture and Economic Capacity 64
12.4 Food-Trade Exposure and Interpretation of Transferable Practices 65
12.5 Geographic Visualization of Selected Country Benchmarks 66
13. Statistical and Econometric Analysis Framework 66
13.1 Analytical Implementation 66
13.2 Data-Quality and Descriptive Layer 67

13.3 Advanced Econometric Diagnostics 68
13.4 Effect Sizes and Uncertainty 68
13.5 Reporting Plan 68
13.6 Completed Climate-Yield Econometric Evidence 68
13.7 Demographic, Trade and Energy-Exposure Analytics 70
13.8 Econometric Results Register and Additional Model Eligibility 71
13.9 Consolidated Economics and Econometrics Results 72
13.10 Full Model-Level OLS Diagnostics and Independent-Use Restrictions 74
14. Integrated Quantitative Synthesis and Publication Outputs 75
15. Future Water-Food-Economic Scenarios: 2030/2040/2050 77
16. Analytical Propositions to be Tested 78
16.1 Consolidated Conclusions and Implications 79
17. Evidence Readiness and Research Priorities 79
18. Current Limitations and Interpretation Guardrails 80
18.1 Publication-Readiness Requirements and Release Controls 82
18.2 Evidence-Validation Boundary and Outstanding Work 82
Editorial Statement for the Current Release 83
Appendix A: Supporting Statistical and Econometric Results 84
Appendix B: Data-Source Summary and Legal/Reuse Notes 86
Appendix C: Supplementary analytical evidence and figure provenance 87
C.1 Econometrics: Fourteen Model-Level Analyses 87
C.2 Farm Economics: Six Commodities 87
C.3 Preservation and Irrigation Economics: AG01, AG02 and AG03 87
C.4 Choropleth Coverage and Spatial Guardrails 87
Data Availability and Reproducibility 88
Declarations 88
About the Authors 89
About This Collaborative Research 90
Glossary and Definitions 91
References 96

1. Introduction and Research Rationale

1.1 Why the Water-Agriculture-Food Nexus Requires an Integrated Study

Food security is often discussed as if it were primarily a production problem. In practice, national food security depends on a longer chain: water availability and reliability, land and soil conditions, crop and livestock productivity, harvest and post-harvest handling, storage, preservation and processing, transport and markets, imports and exports, affordability, nutrition, and household access to safe water. A country may produce a large physical volume of food and still experience high economic losses, import dependence, spatial inequality, seasonal shortages, nutritional gaps or unsustainable pressure on groundwater.

Pakistan is particularly suitable for an integrated water-food analysis because the Indus Basin supports one of the world's largest contiguous irrigation systems and underpins much of the country's agricultural production. FAO has described the Indus Basin irrigation system as the world's largest contiguous irrigation system, while World Bank analysis has emphasized the contrast between the scale of Pakistan's water infrastructure and the relatively low productivity of irrigated agriculture in many settings (FAO, 2018; World Bank, 2019). The scale of the system is therefore not, by itself, a performance measure. The central empirical question is how effectively water is converted into food, economic value and resilience.

The research deliberately avoids assuming that any single country, irrigation system, crop or policy is 'best'. It instead evaluates measurable outcomes: yield per hectare, production stability, water productivity, value per hectare, value per cubic metre, food availability, trade dependence, post-harvest losses, storage performance and exposure to climatic and market risks.

1.2 The 2000-2025 Perspective

A 25-year analytical horizon is long enough to distinguish structural change from short-lived fluctuations, while remaining relevant to present infrastructure, markets and climate conditions. The preferred annual window is 2000-2025. Where harmonized international datasets currently stop in 2024, the actual endpoint is retained rather than extrapolated. Pakistan-specific official statistics can be used to extend selected national series to 2025, provided definitions and time bases are compatible.

Current 2025-26 official information is useful as context rather than as a substitute for the historical panel. For example, the Pakistan Economic Survey 2025-26 reports agriculture at 23.44% of GDP in FY2026 and describes food imports as the second-largest broad import category during July-March FY2026; it also identifies palm oil as a major component of the food import bill (Ministry of Finance, 2026). These recent observations reinforce the importance of connecting agricultural production to trade, prices and food-system economics, but they are analytically separated from the historical calendar-year series.

1.3 From Production to Preservation and Value

The study extends beyond farm production because food that is grown but lost before consumption has already consumed land, water, labor, energy and capital. FAO distinguishes food loss along the production and supply chain before retail from food waste at retail and consumption, and stresses that critical loss points differ by commodity and supply-chain stage (FAO, 2019). In Pakistan, ADB value-chain studies identify storage, transport, packaging, market infrastructure and finance as important post-harvest constraints in horticulture (ADB, 2022; ADB, 2025). Therefore, preservation and storage are treated as productive investments in food security, subject to cost-benefit, energy and technical feasibility analysis.

1.4 Demographic Demand, Economic Capacity and Energy Exposure

Population is not only a denominator for per-capita indicators; it is a forward demand variable. A large and youthful population implies continuing requirements for food, water, housing, education, transport and employment. A low youth-to-old ratio raises a different set of questions about workforce replacement, rural ageing, farm labour and the need for mechanization. The synthesis therefore avoids treating either rapid growth or population ageing as inherently good or bad. The relevant question is whether demographic structure is matched by productivity, human-capital investment, infrastructure and resource availability.

Economic and energy conditions determine how easily that demand can be met. GDP and income influence investment capacity and diet composition; reserves and the current account affect foreign-exchange resilience; and fuel/oil/gas dependence can transmit external price and exchange-rate shocks into irrigation pumping, machinery, fertilizer, transport, cold chains, processing and food distribution. These links are treated as contextual channels to be tested rather than as automatic causal claims.

2. Aims, Objectives and Research Questions

2.1 Overall Aim

To determine how effectively Pakistan has converted its water, irrigation, land and agricultural resource base into food, economic value and resilient supply during 2000-2025; to compare that performance with relevant regional and international benchmarks; and to identify evidence-based pathways for improving future water and food security to 2030, 2040 and 2050.

2.2 Specific Objectives

1. Construct a harmonized 2000-2025 database covering water, irrigation, climate, agriculture, food availability, trade, prices, macroeconomics, post-harvest loss, preservation/storage, WASH and GIS attributes.
2. Measure long-term changes in cultivated area, production, yield, water use, irrigation dependence, food availability, trade exposure and economic productivity.
3. Compare Pakistan with regional peers, water-stressed analogues and higher-productivity/value-add benchmark countries without relying on a single composite ranking.
4. Estimate physical and economic water productivity for major crops and, where data permit, livestock/dairy and food-processing systems.
5. Quantify food import dependence, export earnings, trade-partner concentration and the foreign-exchange implications of essential food commodities, especially edible oils and oilseeds, pulses, cereals, dairy products and other major food groups.
6. Evaluate post-harvest food losses, storage constraints, preservation technologies, cold chains, coatings/films, packaging and processing as components of national food security.
7. Use GIS and remote sensing to spatially relate irrigation, groundwater dependence, water stress, cropping patterns, productivity, WASH access and food-loss/value-chain hotspots.
8. Apply advanced statistical and econometric methods appropriate to repeated country-year and commodity-year observations, with publication-class reporting.
9. Build 2030/2040/2050 scenarios that test the combined effects of productivity gains, irrigation efficiency, crop-mix changes, storage/loss reduction, groundwater constraints and climate stress.
10. Translate the combined evidence into transparent conclusions and policy/investment options only after quantitative analysis is complete.
11. Evaluate Pakistan's progress in crop genetic improvement, commercial biotechnology, biofortification, tissue culture and genome editing, distinguishing research-stage development from regulatory approval and scaled

farm practice, and comparing relevant technology pathways with regional, European and mature global benchmarks.

12. Evaluate the long-run evolution of food-preservation technology and compare Pakistan with relevant international practice in cold chain, storage, packaging, coatings/films, advanced processing, digital monitoring, research maturity and commercial adoption.
13. Quantify how population scale, fertility/age structure, macro-financial capacity, current-account/reserve conditions and oil/gas/fuel-import exposure condition food-system resilience and the capacity to finance water, irrigation, storage, processing and productivity investment.

2.3 Research Questions

Table 2.1: Research questions guiding the integrated synthesis.

ID	Research question
RQ1	How have Pakistan's water resources, irrigation, agricultural production and food-security indicators changed from 2000-2025?
RQ2	How does Pakistan compare with regional peers and selected global benchmark countries on yield, water productivity, economic productivity and food-system resilience?
RQ3	Is Pakistan converting the scale of its irrigation infrastructure into commensurate agricultural and economic productivity?
RQ4	Which crops, horticultural products, livestock/dairy products and essential foods contribute most to domestic food supply, trade value and foreign-exchange exposure?
RQ5	How large are post-harvest food losses and the associated losses of economic value and embedded water?
RQ6	What roles do groundwater dependence, climate variability and water stress play in agricultural performance?
RQ7	How do domestic drinking-water access and agricultural-water systems vary spatially within Pakistan?
RQ8	Which international practices appear transferable to Pakistan under comparable resource, climatic and economic constraints?
RQ9	How might alternative efficiency, loss-reduction, crop-mix and climate scenarios alter water and food security to 2030/2040/2050?
RQ10	How do essential food imports and agri-food exports affect Pakistan's external balance, food-system resilience and exposure to international supply/price shocks?
RQ11	Which storage and preservation systems can reduce physical, nutritional and economic food loss while remaining technically, energetically and financially sustainable?
RQ12	How far has Pakistan progressed in crop genetic improvement, biotechnology, biofortification and genome editing; which developments are already practiced commercially; and how does this compare with relevant regional, European and mature global technology benchmarks?
RQ13	How has food-preservation technology evolved from traditional methods to modern and emerging systems, and where does Pakistan sit relative to international practice in research, adoption and commercialization?
RQ14	How do demographic structure, economic capacity and energy/fuel-import exposure condition Pakistan's ability to finance and sustain water, agricultural productivity, food supply, storage and trade resilience?

3. Conceptual Framework

The thesis treats food security as an interacting system rather than a single production indicator. The causal sequence is not strictly linear: prices affect crop choices, trade changes domestic availability, water stress changes yields, storage changes seasonal prices, and preservation can influence exportability and farmer returns. Nevertheless, the following analytical chain provides the organizing framework.

Table 3.1: Conceptual layers linking resources, production, retention, markets and water-food security outcomes.

Layer	Core components	Analytical role
1. Resource base	Surface water; groundwater; precipitation; climate; land; soils	Defines physical opportunity and constraint.
2. Agricultural conversion	Irrigation delivery; crop area; livestock; inputs; technology; yields	Converts resources into biological output.
3. Post-harvest retention	Harvesting; handling; storage; cold chain; preservation; processing; packaging	Determines how much produced food remains saleable, safe and nutritious.
4. Markets and trade	Domestic prices; imports; exports; market access; logistics; value addition	Determines affordability, foreign-exchange effects and producer incentives.
5. Demographic, macro-financial & energy context	Population; fertility/age structure; GDP/income; debt/reserves/current account; oil/gas and fuel-trade exposure	Conditions demand growth, labour availability, input/logistics costs and investment capacity.
6. Food and water security outcomes	Availability; stability; nutritional supply; household water access; resilience	Represents the social and economic outcomes of the system.
7. Future resilience	Climate change; population; groundwater constraints; investment; technology	Determines whether the system remains viable to 2030/2040/2050.

Cross-cutting analytical lenses are GIS/remote sensing, statistical inference, econometrics, uncertainty analysis, and source/provenance auditing. The framework therefore links physical water accounting to biological production, post-harvest science and national economics rather than treating these as separate subjects.

A cross-cutting innovation pathway is now explicit in the framework: conventional and molecular breeding, marker-assisted selection, biofortification, tissue culture, genetically modified crops and genome editing. These technologies can affect yield, resistance, post-harvest quality, nutrient density and input demand, but they are evaluated at distinct stages of maturity: research, confined/field testing, regulatory approval, varietal release, commercial seed multiplication and widespread farmer adoption. Another food-technology innovation pathway is now tracked across post-harvest handling, refrigeration, atmosphere control, packaging, coatings/films, thermal and non-thermal processing, sensing and digital shelf-life management. Technology maturity is recorded separately from demonstrated Pakistan adoption.

Demography and macro-financial/energy exposure are additional cross-cutting conditions. They do not replace the physical water-food chain, but they influence the scale and composition of demand, the availability of labour and capital, and the cost of moving water and food through energy-intensive stages such as pumping, fertilizer supply, processing, cooling and transport. These conditions are therefore carried into comparator analysis and future scenarios.

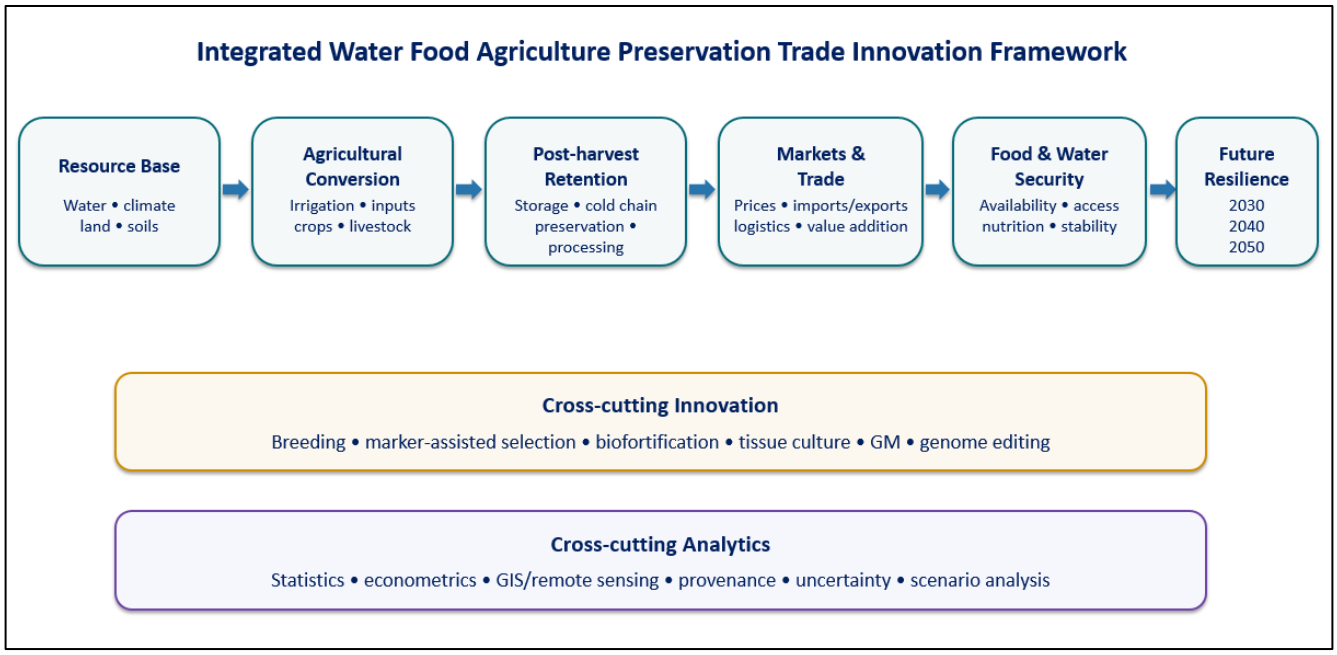


Figure 3.1: Integrated water-food-agriculture-preservation-trade-innovation conceptual framework.

Interpretation: *Food security is an end-to-end conversion problem: resources must be converted into biological output, retained after harvest, moved through markets and trade, and translated into stable food and water-security outcomes.*

4. Data Architecture, Sources and Provenance

4.1 Core Analytical Structure

The preferred analytical architecture is a relational set of long-form tables rather than one extremely wide data table. The central tables are: Country-Year, Country-Year-Commodity, Pakistan Province/District-Year, Food Trade by Partner, Preservation/Storage Evidence, Food-Loss Evidence, GIS Attributes and Scenario Parameters. Every derived metric preserves links to the underlying source fields.

Table 4.1: Core analytical domains, source families, variables and temporal treatment.

Domain	Primary source families	Key variables	Temporal note
Agricultural production	FAOSTAT; MNFSR; PBS	Area harvested, production, yield; crop/horticulture/livestock variables	2000-2025 where available
Water and irrigation	FAO AQUASTAT; WaPOR; Pakistan official sources	Withdrawals, irrigation, groundwater/surface water, ET, water productivity	Latest harmonized observation + annual remote-sensing where available
Macroeconomics	World Bank WDI; Pakistan Economic Survey; PBS	Population, GDP, agriculture value added, employment, inflation/deflators	2000-2025
Trade and prices	FAOSTAT Trade/Producer Prices; PBS External Trade	Imports, exports, partners, values, quantities, unit values, producer prices	2000-2025 (FAOSTAT trade currently through 2024; PBS can extend Pakistan)
Climate	World Bank CCKP/CRU; ERA5 or equivalent; PMD where reusable	Rainfall, temperature, drought/heat indicators	2000-2025 + future projections
Water stress	WRI Aqueduct 4.0	Baseline/current/future water-stress indicators	Use as screening/prioritization; validate locally
Food loss	FAO FLW Database; SOFA 2019; ADB/Pakistan studies	Loss rates by commodity, stage and method	Study-specific
Preservation/storage	FAO/Codex/WHO; scientific literature; Pakistan value-chain evidence	Temperature, RH, moisture, shelf life, loss reduction, energy, cost	Study/product-specific
WASH	PBS Population & Housing Census 2023; complementary JMP where appropriate	Drinking-water source/access and related household indicators	2023 cross-section; trends from compatible sources only
GIS	GMIA; GMIE-100; WaPOR; WRI; geoBoundaries/PBS boundaries	Irrigation footprint, source dependence, productivity, stress, administrative joins	Multiple vintages; crosswalk required
Crop genetics / biotechnology	Pak-EPA/Pak-BCH; PARC/NIGAB; HarvestPlus; ICAR; FSANZ; USDA/CFIA/CTNBio; EU NGT sources	Commercial GM crops; breeding/biofortification; tissue culture; gene editing; regulatory/adoption status	Current-status evidence + dated technology milestones; not treated as annual panel unless data support
Demography	UN Population Division / UN WPP; UNFPA; World Bank	Population; fertility; age structure; youth-to-old and dependency ratios; sex structure	2025 snapshot + historical series where available
Macro-financial & energy exposure	World Bank WDI/WTO; Energy Institute/EIA via OWID; UN Comtrade/WITS	GDP/income; debt; reserves; current account; merchandise trade; fuel shares/bill proxies; oil/gas production, consumption and import dependence; exact-HS energy trade	Latest available years retained; mixed-year proxies and partial HS coverage explicitly flagged

4.2 Provenance and Reproducibility Requirements

- Every imported series retains organization, dataset name, table/indicator code, URL/DOI, version, download date, unit and geographic level.
- Original and derived fields are distinguishable; transformations are formula-documented.
- Calendar-year, fiscal-year and crop-year observations are not merged without an explicit alignment rule.
- International and Pakistan official series are compared for definition consistency before substitution or splicing.

4.3 Consolidated Analytical Dataset and Harmonization Protocol

The research retains the original national synthesis and analytical datasets as auditable source records. New analysis uses derivative, model-specific extracts, without silently overwriting original observations. The global trade, macro-financial, demographic and physical-energy files supply context and cross-country comparisons; they are not automatically a longitudinal panel. The Pakistan GIS master file and the revised GIS package supply spatial attributes and geometries at the precision actually available.

Harmonization requires a composite country-year-variable key (or commodity/year or district/year, as appropriate), explicit source vintage, units, deflator and currency basis, missing-value status, derived-variable formula and coverage flag. World totals are not computed by adding partial-coverage country rows. Likewise, broad fuel-trade proxies are not interpreted as exact HS-code trade totals; unreported components remain missing rather than being filled with zero.

- Spatial layers retain CRS, resolution, data vintage, processing steps and administrative-boundary crosswalks.
- Food-loss estimates from literature are treated as study evidence with uncertainty, not as precise annual national observations unless the source design supports that interpretation.
- Data-use and reuse conditions are recorded, particularly for national datasets and any restricted meteorological or spatial products.

5. Literature Synthesis and Knowledge Gaps

5.1 Water Productivity Rather than Infrastructure Scale

The literature consistently indicates that Pakistan's water challenge is not explained by physical scarcity alone. World Bank analysis emphasizes irrigation service delivery, allocation, on-farm water management, crop choice and agricultural market incentives as important determinants of productivity (World Bank, 2019). The World Bank's agriculture-food-system knowledge program similarly links long-run agricultural performance to markets, public spending, innovation and the need for more water-efficient, higher-value agriculture (World Bank, 2022). This supports a research design that measures outputs per hectare and per unit of water, not only total production.

5.2 Food Security as Availability, Access, Utilization and Stability

National food availability is necessary but insufficient for food security. The thesis therefore combines food-production indicators with trade, prices, losses and WASH. Current Pakistan official reporting separately tracks per-capita availability of cereals, pulses, milk, meat, fish, eggs, edible oil/ghee, fruits and vegetables, sugar and calories, illustrating the need for a broader food basket rather than a cereal-only approach (Ministry of Finance, 2026).

5.3 Post-Harvest Loss and Value-Chain Constraints

FAO's global food-loss framework stresses that loss estimates vary widely by commodity, geography and supply-chain stage, so intervention design needs to focus on verified critical loss points rather than a single national percentage (FAO, 2019). Pakistan-focused ADB work on horticulture reports weaknesses in storage, transport, packaging, market infrastructure and finance, and more recent work assesses onion, tomato and potato value chains with explicit

attention to production cost and post-harvest loss (ADB, 2022; ADB, 2025). This thesis, therefore, distinguishes physical loss, quality downgrade, rejection, price loss and avoidable waste.

5.4 Food Trade and External Vulnerability

Food imports can stabilize domestic supply but also expose the economy to international prices, exchange-rate movements and partner concentration. Conversely, agricultural exports generate foreign exchange but can create domestic trade-offs when exportable commodities compete for scarce water or land. The economic analysis examines gross trade flows, net trade value, import dependency, self-sufficiency, unit values, partner concentration and water/economic productivity together. Edible oils and oilseeds are a core case because recent official reporting highlights their large role in Pakistan's food import bill (Ministry of Finance, 2026).

5.5 Demographic Transition, Food Demand and the Agricultural Workforce

Demographic pressure is not captured by total population alone. Fertility, age structure and the ratio of younger to older people influence the timing of future food demand, labour-force growth and dependency. A young population can become a productive demographic dividend only when health, education, skills, jobs and infrastructure expand with it; otherwise the same age structure can intensify pressure on food, water and public services. At the other extreme, ageing can reduce agricultural labour availability and increase the value of mechanization, automation and labour-saving logistics.

Diet composition also changes with income and urbanization, so future demand cannot be represented by headcount alone. Higher incomes can shift demand toward dairy, animal protein, edible oils, fruit, vegetables, processed foods and cold-chain services. The scenario framework therefore treats population, age structure and diet composition as interacting demand drivers rather than a single population-growth multiplier.

5.6 Energy and Macro-Financial Exposure as Food-System Multipliers

Agriculture and food systems are exposed to energy through irrigation pumping, machinery, fertilizer and agrochemical supply, processing, refrigerated storage, transport and retail distribution. A country can therefore experience higher food costs or weaker investment capacity even when domestic crop output is unchanged. The completed global financial-trade workbooks now allow this channel to be measured using broad merchandise/fuel exposure, current-account and reserve context, together with physical oil/gas dependence. These metrics are used as contextual vulnerability indicators; broad fuel-dollar figures are proxies, and exact HS oil/gas trade is used only where component coverage is documented.

5.7 Crop Genetic Improvement, Biotechnology and Advanced Breeding

Pakistan's crop-innovation landscape is mixed rather than technologically uniform. Commercial genetically modified cotton is an established component of the crop system, while NIGAB/PARC report broader GM and genome-editing research in wheat, potato, tomato, groundnut and other crops that cannot be described as commercial farm adoption until regulatory and deployment evidence supports that conclusion. Other scaled innovations are non-GM: zinc-biofortified wheat, tissue-culture banana and molecular/phenotypic characterization of mango germplasm demonstrate that genetic improvement extends well beyond transgenic crops. The international comparison therefore distinguishes commercial biotechnology leaders, countries moving genome-edited crops toward release, and the more precautionary European regulatory trajectory. This distinction is important because laboratory capability, varietal release, regulatory authorization and widespread adoption are different outcomes.

5.8 Knowledge Gap Addressed by This Thesis

Many existing studies are strong within one domain-irrigation engineering, crop productivity, trade, nutrition, WASH, horticulture losses or climate risk-but fewer connect these domains quantitatively over a common 25-year

framework. The main contribution of this synthesis is integration: the same evidence base is used to evaluate water, production, preservation, trade, economics and future resilience, while maintaining transparent source lineage and statistical uncertainty.

6. GIS and Remote-Sensing Framework

6.1 Spatial Role in the Thesis

GIS supplies the spatial linkage between the physical irrigation network, groundwater dependence, climate exposure, crop productivity, food-loss concerns and drinking-water access. Instead of repeating an atlas here, the figures are embedded where their subject is analyzed: Chapter 7 presents irrigation and climate, Chapter 8 presents crop productivity and food-loss concepts, and Chapter 11 presents WASH. This chapter documents the integrated spatial scope and the reusable geographic data structure.

Table 6.1: Fourteen Pakistan GIS map products in the current spatial programme.

Map	Product	Purpose
M01	Pakistan irrigation extent / network	Core irrigation footprint and infrastructure context
M02	Groundwater vs surface-water irrigation	Spatial dependence on groundwater, surface water or mixed sources
M03	Modern irrigation footprint - GMIE-100	Current high-resolution irrigated-area footprint
M04	Water stress + irrigated agriculture overlay	Irrigated production exposed to elevated water stress
M05	Improved drinking-water access by district	Census 2023 WASH spatial access
M06	Households without improved drinking water	Absolute and percentage WASH burden
M07	Indus Basin / major rivers / dams / barrages / canal context	Hydrological and irrigation-system reference map
M08	Crop-water productivity (WaPOR)	Physical/biomass water productivity where extraction is methodologically compatible
M09	Crop yield vs irrigation intensity	District/province productivity relative to irrigation footprint
M10	Food-loss / embedded-water hotspots	Later-stage integration of production, loss evidence and water productivity
M11	FAO GAEZ agro-ecological / agricultural-potential framework	National agro-ecological or agricultural-potential context using selected FAO GAEZ v5 classes/indicators
M12	Annual rainfall by GAEZ analysis zone	Area-aware CHIRPS annual rainfall summaries by GAEZ zone/class
M13	Monthly / seasonal rainfall by GAEZ analysis zone	Seasonal and monthly rainfall structure for agro-ecological interpretation
M14	Rainfall variability / trend / drought by GAEZ analysis zone	Historical variability, anomalies and trend/drought screening using 1981-2025 CHIRPS extraction

6.2 Temporal Spatial Analysis

The GIS series uses the original identifiers M01-M14 for data management, while the manuscript uses continuous figure numbering within each chapter. M05, M06 and M09 are sourced provincial GIS compositions; M07 is a partial infrastructure reference. M01-M04, M08 and M10-M14 are illustrative designs informed by the stated reference sources rather than verified quantitative spatial extractions. Their appearance in the discussion is conceptual and cannot be treated as measured spatial results.

6.3 Spatial Integration Across the Research Chapters

The spatial analysis is organized around the research questions rather than around map identifiers. The hydrological network and the irrigation-source and water-stress concepts are discussed in Sections 6.1-6.5; crop-water productivity, provincial wheat performance and food-loss concerns are discussed in Sections 7.2-7.3; and the two

Census 2023 drinking-water maps appear with the provincial WASH evidence in Section 11.1. The map-product register above retains the M-series identifiers to link the figures to their source tables and future GIS workflows.

6.4 Spatial-Data Integration and Reusable Outputs

The reusable package contains province-level boundaries, the available major-river geometries, infrastructure attributes and coordinates, WASH data and wheat-yield/irrigation comparison tables. Additional spatial extraction would be needed to turn the illustrative irrigation, WaPOR, GAEZ, CHIRPS and food-loss concepts into measured geographic outputs.

6.5 Interpretation Across Spatial Scales

Maps are used at the spatial resolution supported by their underlying records. Provincial figures identify broad differences but cannot resolve district or canal-command variation; conceptual geographic illustrations help communicate research questions but are not substitutes for source-derived, georeferenced spatial observations. The integrated evidence is therefore interpreted alongside the numerical analyses in the preceding chapters.

The spatial data package retains province boundaries, major river geometries, selected infrastructure coordinates and GIS-ready tabular attributes. The map register and the underlying original datasets remain available as supplementary research material.

7. Pakistan Water Resources, Irrigation and Groundwater Context

7.1 The Indus Basin as the Production Backbone

The Indus Basin Irrigation System is central to Pakistan's agricultural geography. FAO has characterized the system as the world's largest contiguous irrigation system and has linked climate-resilient agriculture in the basin to water-management reform and climate information (FAO, 2018). The thesis uses this scale as a starting condition, not as evidence of efficiency.

The geographic reference in Figure 7.1 establishes the principal river, storage and diversion infrastructure on which the discussion of irrigation relies. Figure 7.2 then places that infrastructure within the broader, generalized irrigation footprint. The two figures need to be read together: one identifies the physical network, while the other depicts its agricultural context.

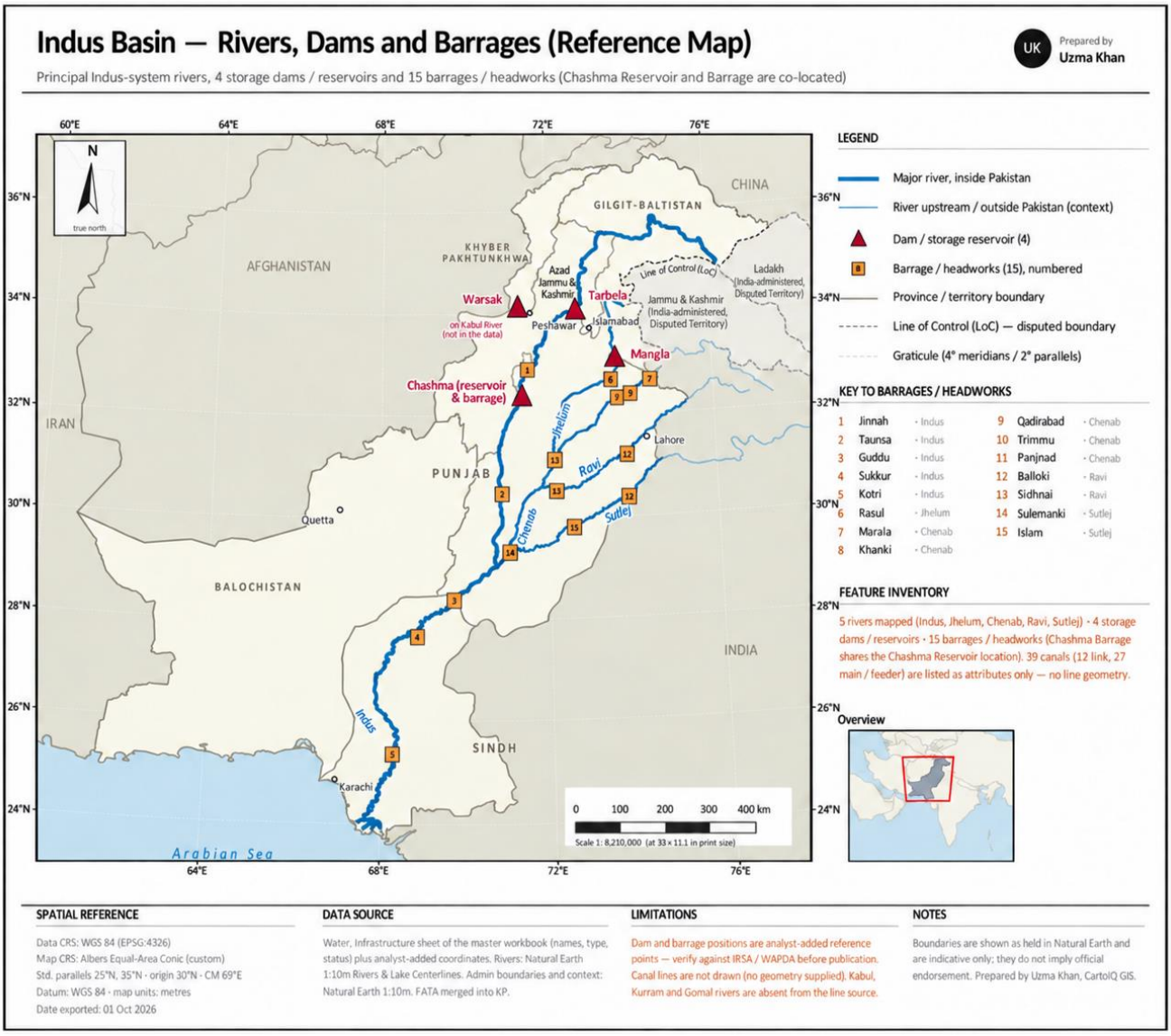


Figure 7.1: Indus Basin: principal rivers, selected dams and barrages.

The network map identifies the main river and diversion corridors, but the canal lines are not fully mapped in the available geographic inventory. It therefore supports a national-scale infrastructure discussion without implying a complete distributary inventory.

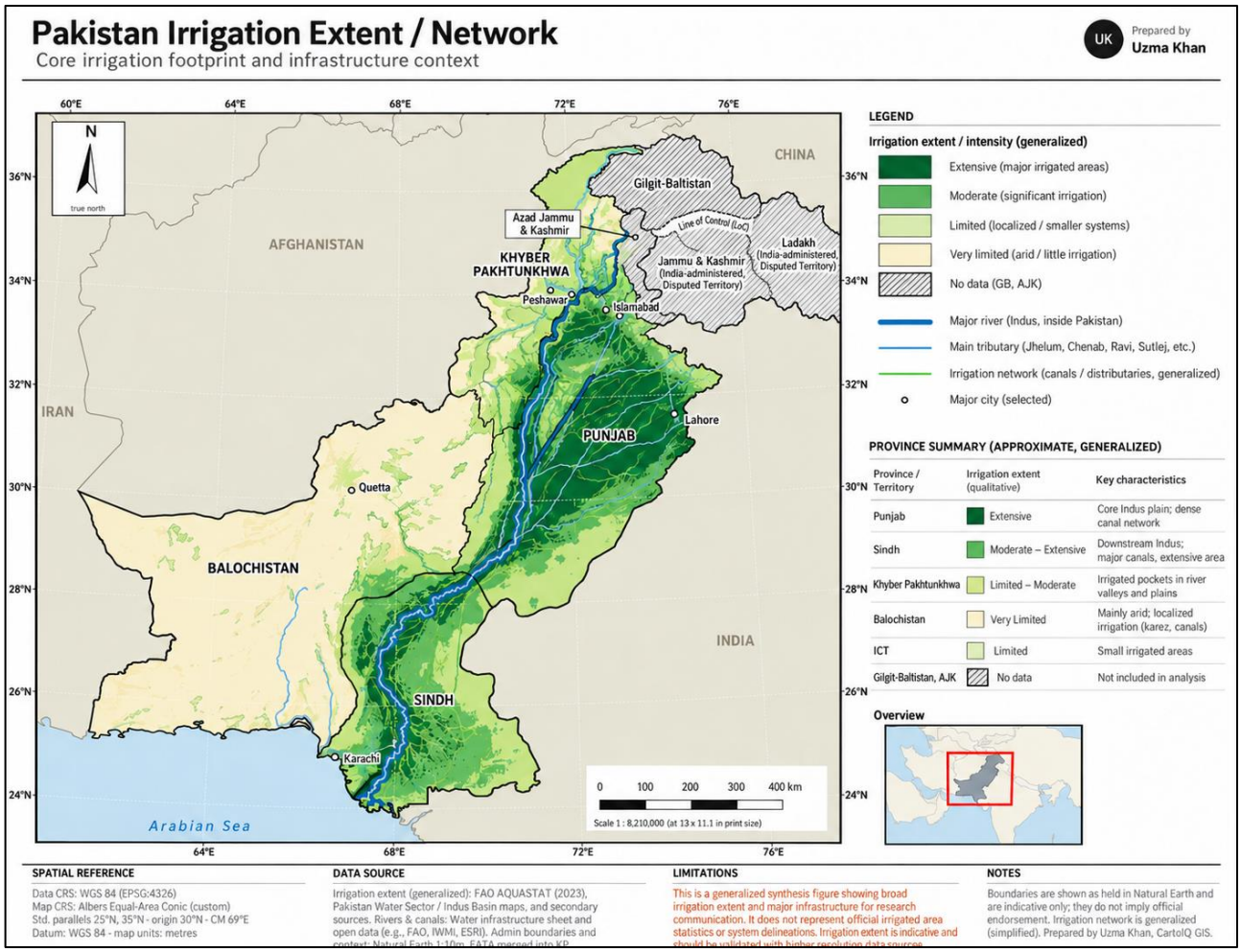


Figure 7.2: Generalized irrigation extent and canal-network context in Pakistan.

The predominance of irrigated agriculture along the Indus plain explains why dependable river delivery, canal maintenance and upstream storage are central to national food production. The shading depicts the conceptual footprint, not measured pixel-level irrigation extent.

7.2 Surface Water, Groundwater and Conjunctive Use

Agricultural production depends on both canal supplies and groundwater pumping. The analytical task is to distinguish where groundwater complements unreliable or insufficient canal water from where groundwater abstraction itself represents an emerging sustainability risk. AQUASTAT, Pakistan official sources, remote sensing and, where methodologically appropriate, groundwater-storage evidence are integrated to characterize this dependence.

Surface-water command areas and groundwater-based irrigation are spatially interdependent. Figure 7.3 illustrates the principal source categories and the zones where conjunctive use is relevant; it is not a measured district-by-district allocation of water withdrawals.

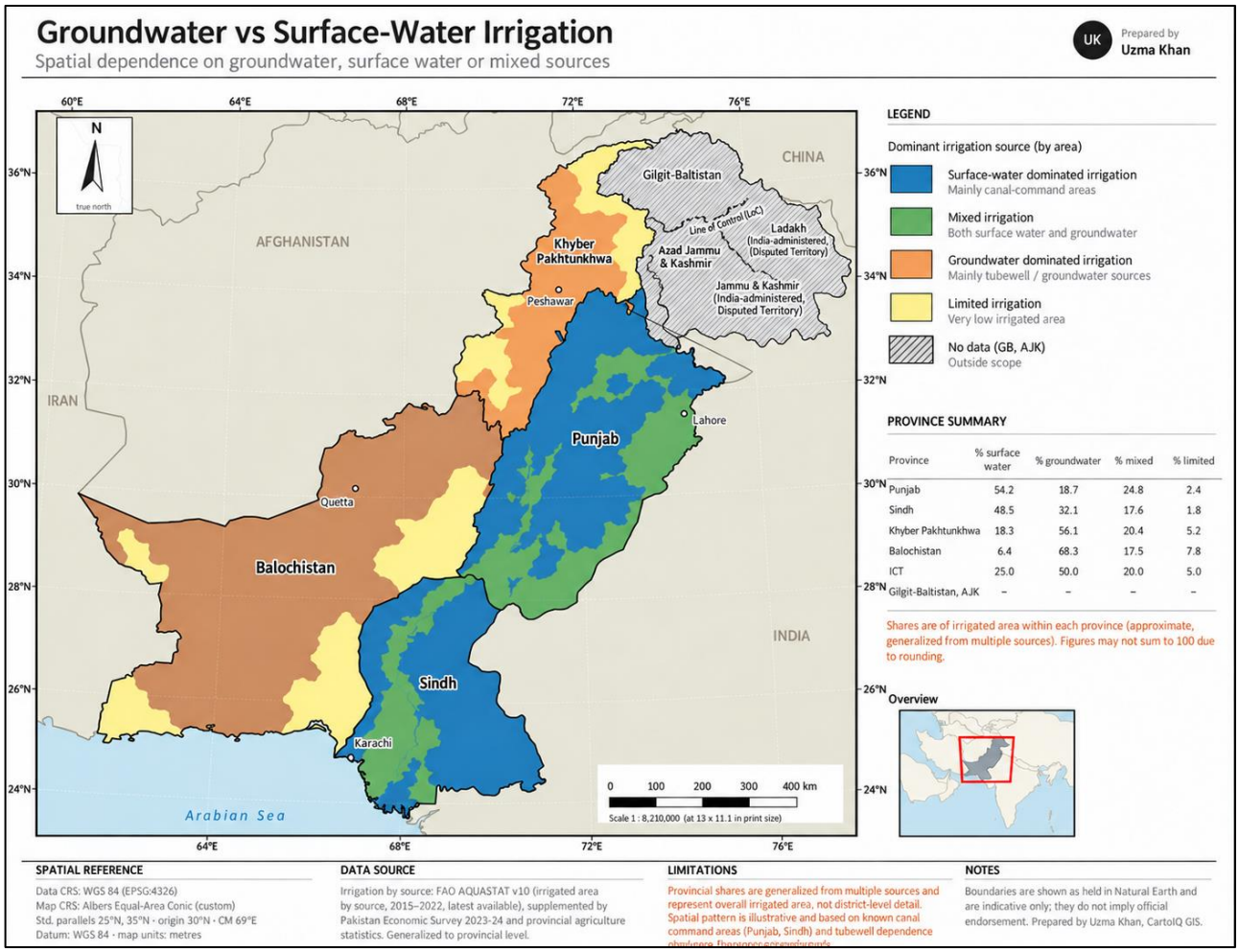


Figure 7.3: Conceptual distribution of surface-water, groundwater and mixed irrigation sources.

The central analytical distinction is between complementary groundwater use, which may buffer variable canal deliveries, and persistent dependence on abstraction where aquifer replenishment cannot be assumed. This distinction is important when interpreting water productivity and long-term agricultural resilience.

7.3 Irrigation Efficiency and Economic Productivity

Physical efficiency and economic productivity are different. A system can reduce conveyance or application loss yet still allocate water to low-value or poorly performing uses. The thesis distinguishes engineering/physical efficiency from crop water productivity (kg/m3) and economic water productivity (USD/m3). Water-productivity analysis uses evapotranspiration-based indicators, where possible, and withdrawal-based indicators only with explicit labeling because the two denominators are conceptually different.

Water withdrawal and water consumption are not interchangeable. Withdrawal is the volume taken from rivers, reservoirs, lakes or aquifers for agriculture, industry or domestic use; some of this water may return to the system as drainage or treated wastewater. Consumption is the portion not returned for immediate downstream reuse, principally through evaporation, crop transpiration or incorporation into products. For example, withdrawing 100 m^3, consuming 60 m^3 and returning 40 m^3 means a withdrawal of 100 m^3 but consumption of 60 m^3. The return flow is not necessarily recoverable at the same place, time or quality.

The distinction between an equipped irrigation footprint and efficient resource conversion is further illustrated by Figure 7.4. Here, 'modern irrigation' is a conceptual spatial category; the figure does not establish measured uptake of drip or sprinkler systems.

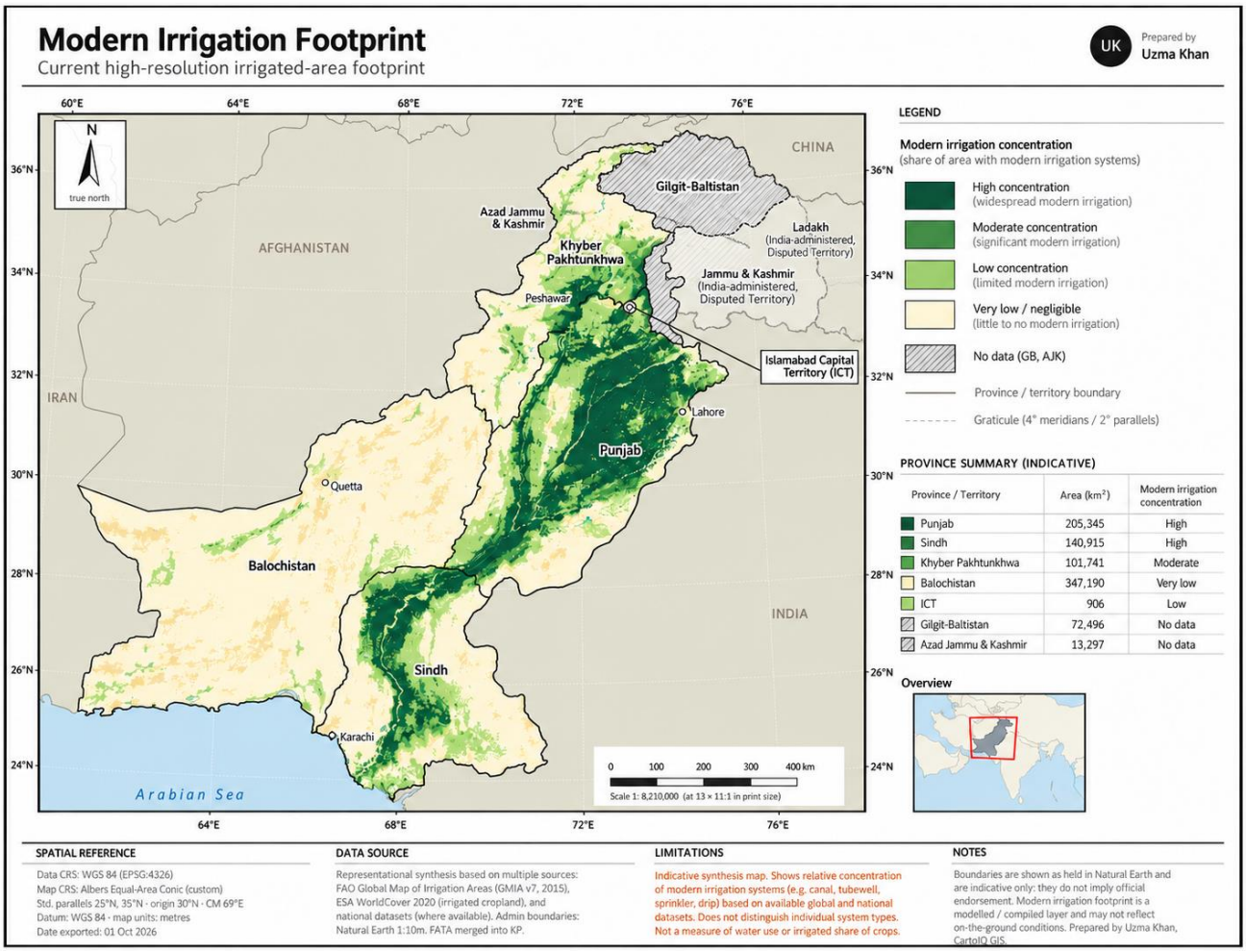


Figure 7.4: Conceptual distribution of the modern irrigation footprint.

The apparent concentration of irrigated agricultural land does not itself demonstrate high water-use efficiency. Evaluating efficiency requires comparable water-input, evapotranspiration, yield and economic-value measurements.

7.4 Climate and Hydrological Risk

Historical climate analysis are based on temperature and precipitation series at national and, where possible, subnational scale. Future scenarios are draw on recognized climate projections rather than extrapolating historical climate mechanically. World Bank Climate Change Knowledge Portal resources provide observed climatology and projected climate context for Pakistan, while WRI Aqueduct provides water-stress indicators that can be used for comparative screening rather than as a substitute for local basin analysis (World Bank CCKP; WRI, 2026).

The 2000-2025 national climate series provides a measured temporal baseline (Figure 7.5) before the spatial climate and agro-ecological context is considered. Keeping the temporal chart ahead of the geographic figures separates observed trends from the illustrative spatial classifications.

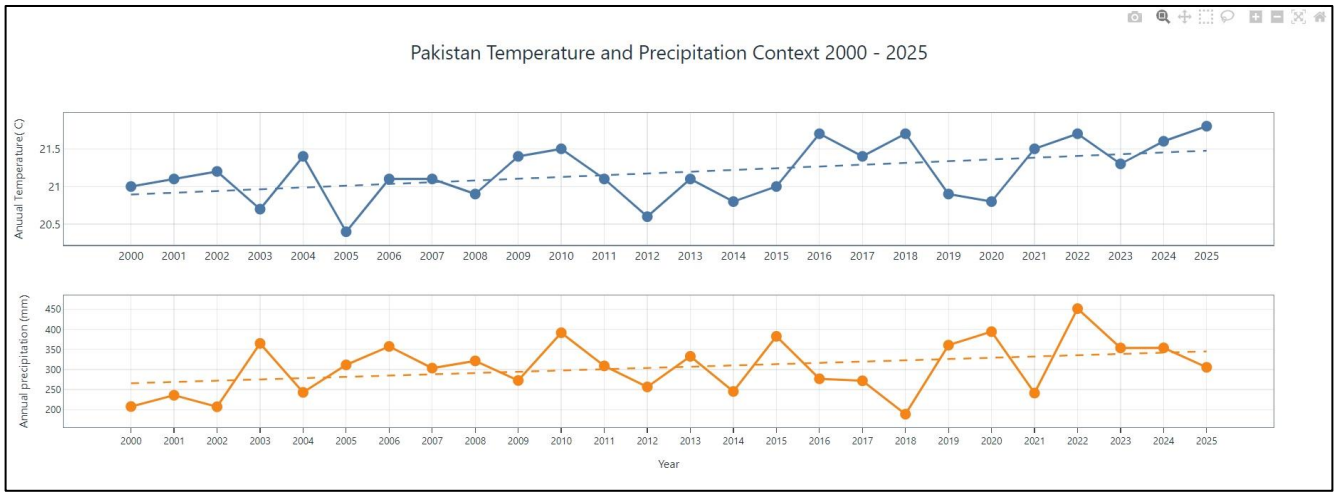


Figure 7.5: Pakistan annual Mean temperature and precipitation, 2000-2025.

The series indicates a positive long-run temperature trend, whereas annual precipitation is variable without a similarly robust monotonic trend in the existing results. Rainfall timing and its interaction with irrigation reliability are therefore relevant to the subsequent spatial analysis.

Agro-ecological conditions influence the interaction of climate, soils, terrain and irrigation. Figure 7.6 introduces the broad geographical framework in which rainfall amount (Figure 7.7), rainfall seasonality (Figure 7.8) and variability or drought exposure (Figure 7.9) can subsequently be evaluated. These four spatial figures are conceptual until the underlying GAEZ/CHIRPS layers are extracted and validated.

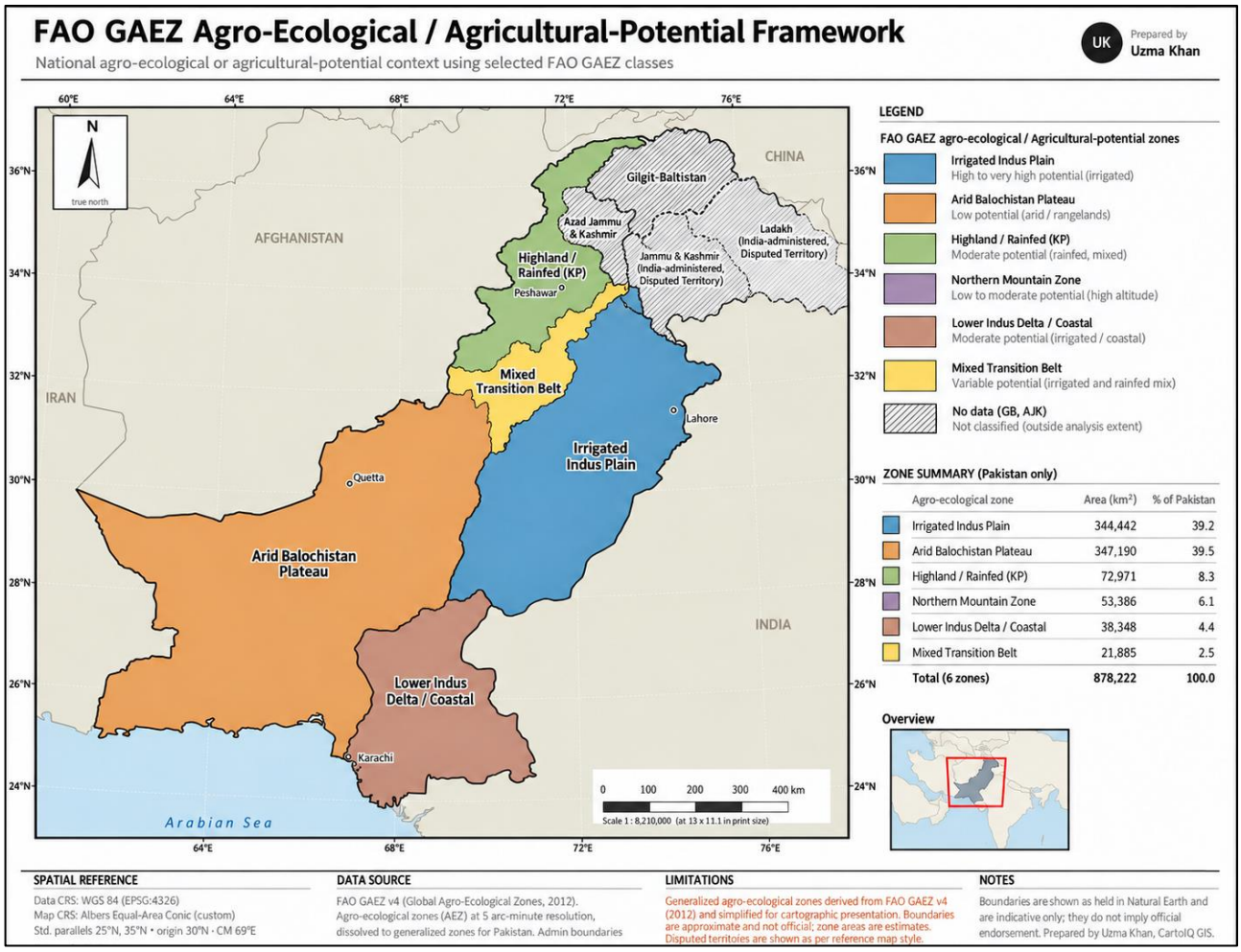


Figure 7.6: Agro-ecological and agricultural-potential zones: conceptual framework.

The broad contrast between the irrigated Indus plain, arid western areas, highland environments and transition zones motivates region-specific assessment rather than treating Pakistan as one homogeneous agricultural landscape.

Annual rainfall is one determinant of crop suitability, but the same yearly total may support different cropping systems depending on its seasonal distribution and the availability of storage or irrigation.

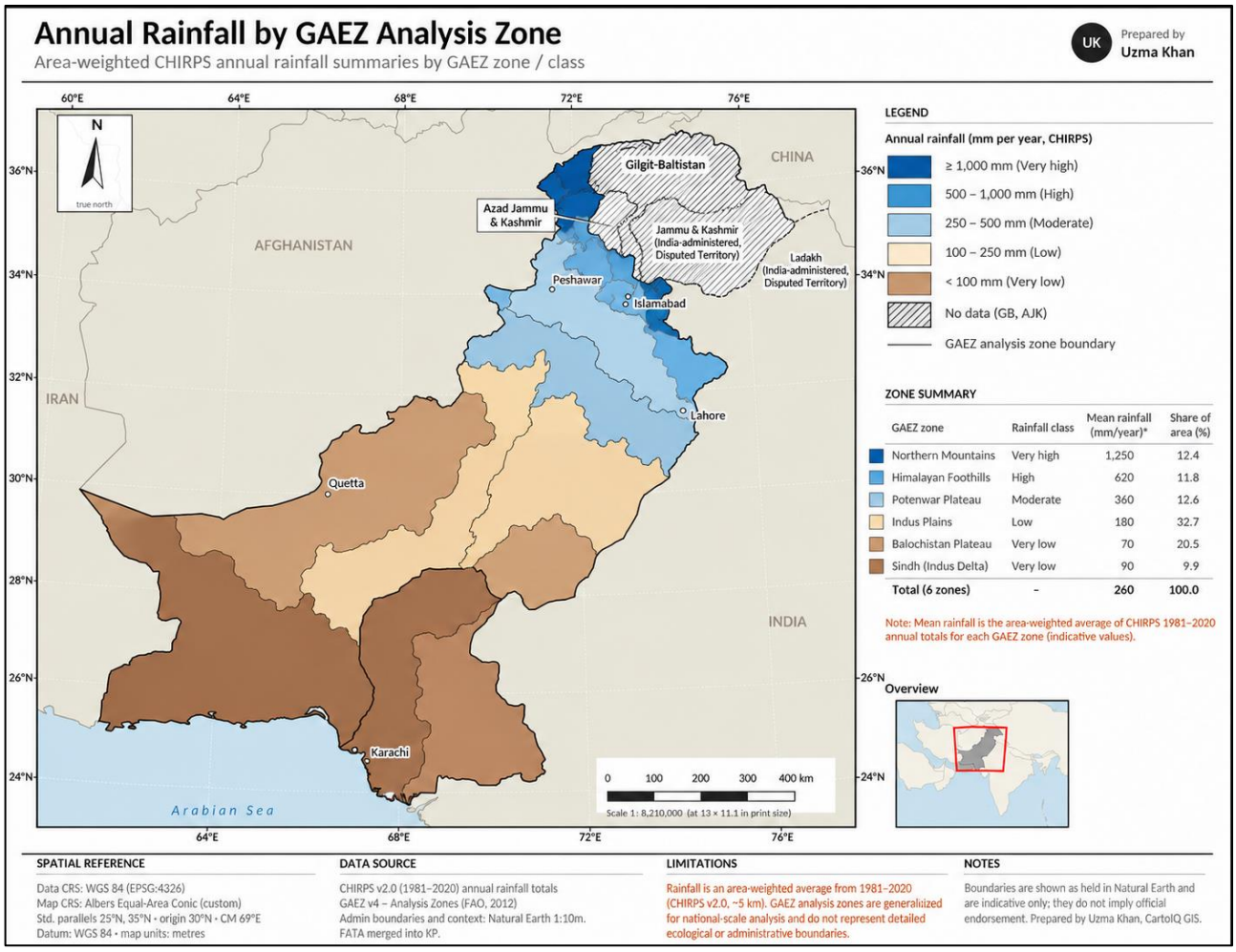


Figure 7.7: Indicative annual-rainfall classes by broad agro-ecological zone.

The map represents broad wet-to-dry regional contrasts. Exact rainfall averages, zone areas and gradients requires extraction from the original precipitation grid before quantitative comparison.

The timing of rainfall matters particularly where crop growth depends on seasonal precipitation or where canal supplies do not coincide with the period of greatest demand.

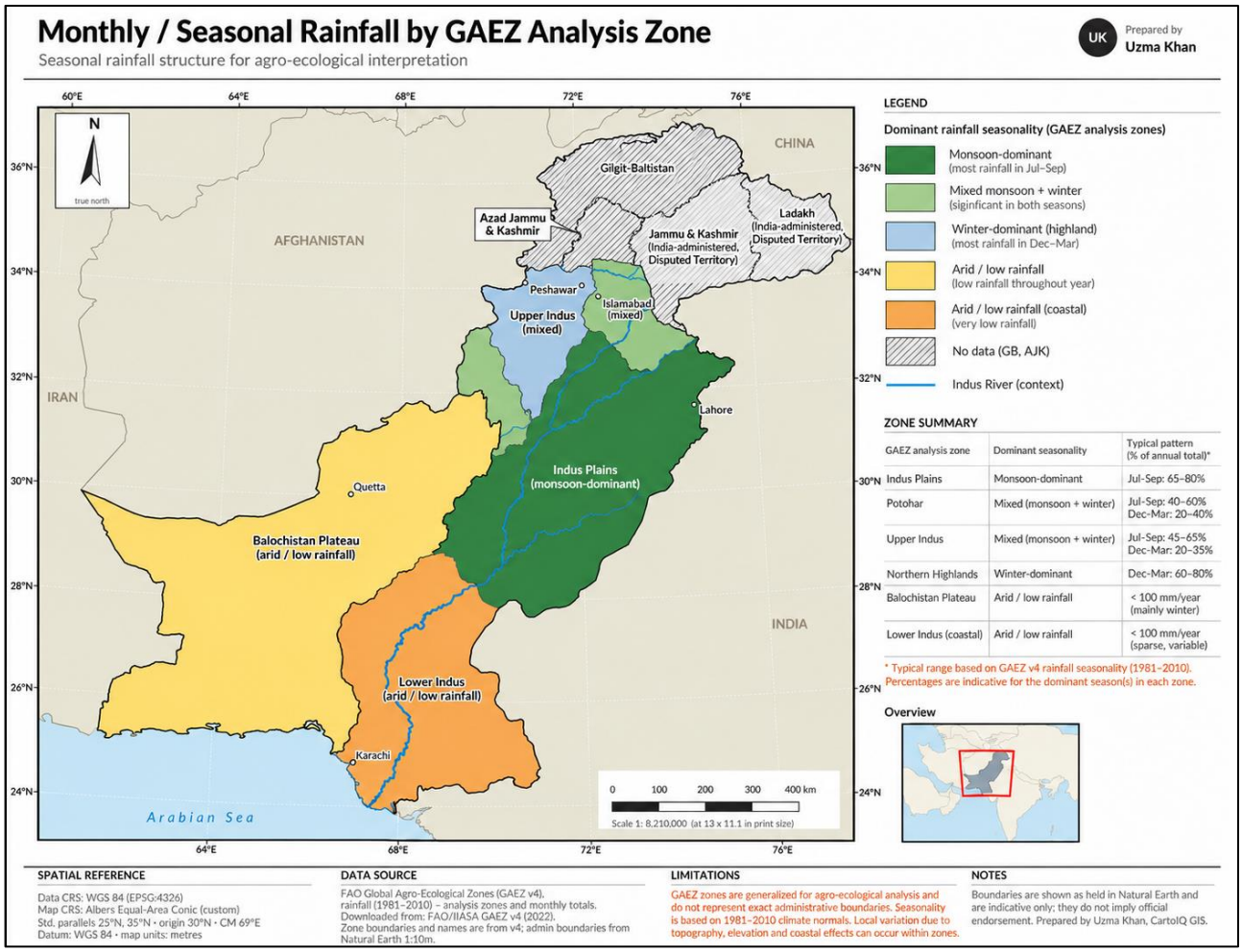


Figure 7.8: Indicative rainfall seasonality by broad agro-ecological zone.

The geographic framework differentiates broadly monsoon-influenced, mixed-season and arid rainfall regimes. It provides a rationale for using seasonal variables in subsequent crop-climate models rather than relying only on annual aggregates.

Interannual variability is distinct from mean rainfall: a dry region can have a relatively stable low baseline, while a wetter region may be exposed to larger deviations between years.

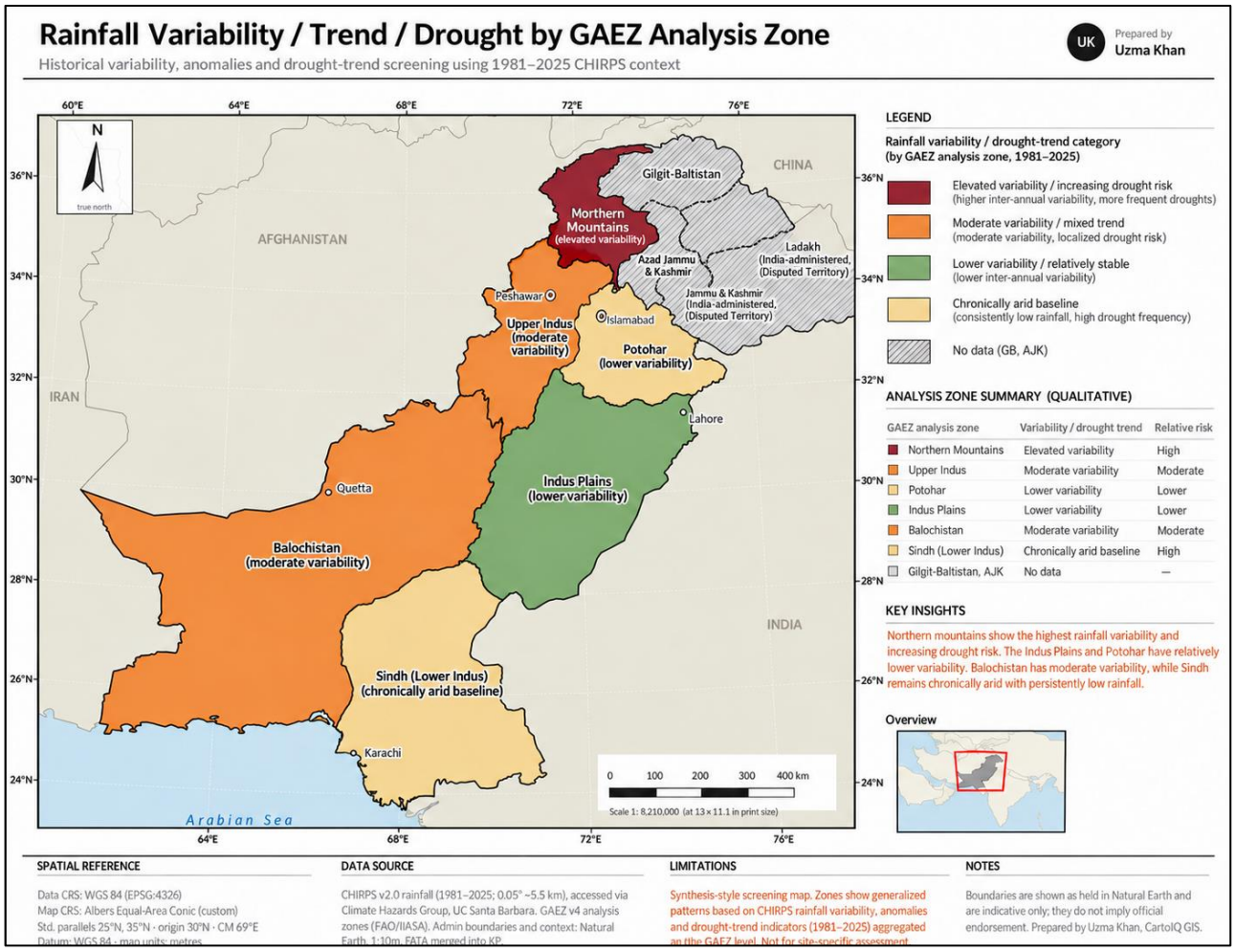


Figure 7.9: Conceptual rainfall-variability and drought-screening zones.

This figure identifies questions for formal anomaly, variability and drought-trend testing; its categories cannot be interpreted as measured increases or decreases in drought frequency.

7.5 Current Quantitative Water and Climate Evidence

The current comparator evidence reinforces the study's central distinction between infrastructure scale and productivity. Pakistan's 2023 water-stress indicator is 98.1%, compared with a 16-country median of about 60.4%. Internal renewable freshwater is approximately 226 m3 per person compared with a comparator median of about 699 m3, while whole-economy water productivity is about USD 2.23/m3 compared with a median near USD 11.95/m3. Agricultural value added per worker is similarly below the comparator median, even though the share of agricultural land reported as irrigated is among the highest in the available sample. These cross-sectional contrasts do not establish causation, but they define the productivity gap that later crop-water and economic analyses must explain.

Interpretation of the two chart indicators. The left panel, labelled ‘water stress’, uses annual freshwater withdrawals divided by internally generated renewable freshwater resources, expressed as a percentage. It describes pressure relative to domestic renewable water, not the proportion of all available water consumed; in countries receiving substantial inflows across borders, the denominator does not include those external inflows. It cannot be confused with the SDG 6.4.2 water-stress indicator, which uses freshwater withdrawals relative to available freshwater resources after environmental-flow requirements. The right panel presents whole-economy water productivity: GDP divided by total annual freshwater withdrawals (USD/m³), using the GDP valuation and price basis stated in the underlying source. For illustration, US$200 billion of GDP divided by 100 billion m³ of withdrawals equals US$2/m³.

This economy-wide indicator reflects economic structure as well as water use; it does not measure irrigation efficiency or the economic return attributable to each cubic metre of water.

Figure 7.10 overlays the concepts of irrigated production and water stress to show why exposure needs to be considered jointly rather than through irrigation area alone. The quantitative cross-country context is reported separately in Table 7.1 and Figures 7.11-6.12.

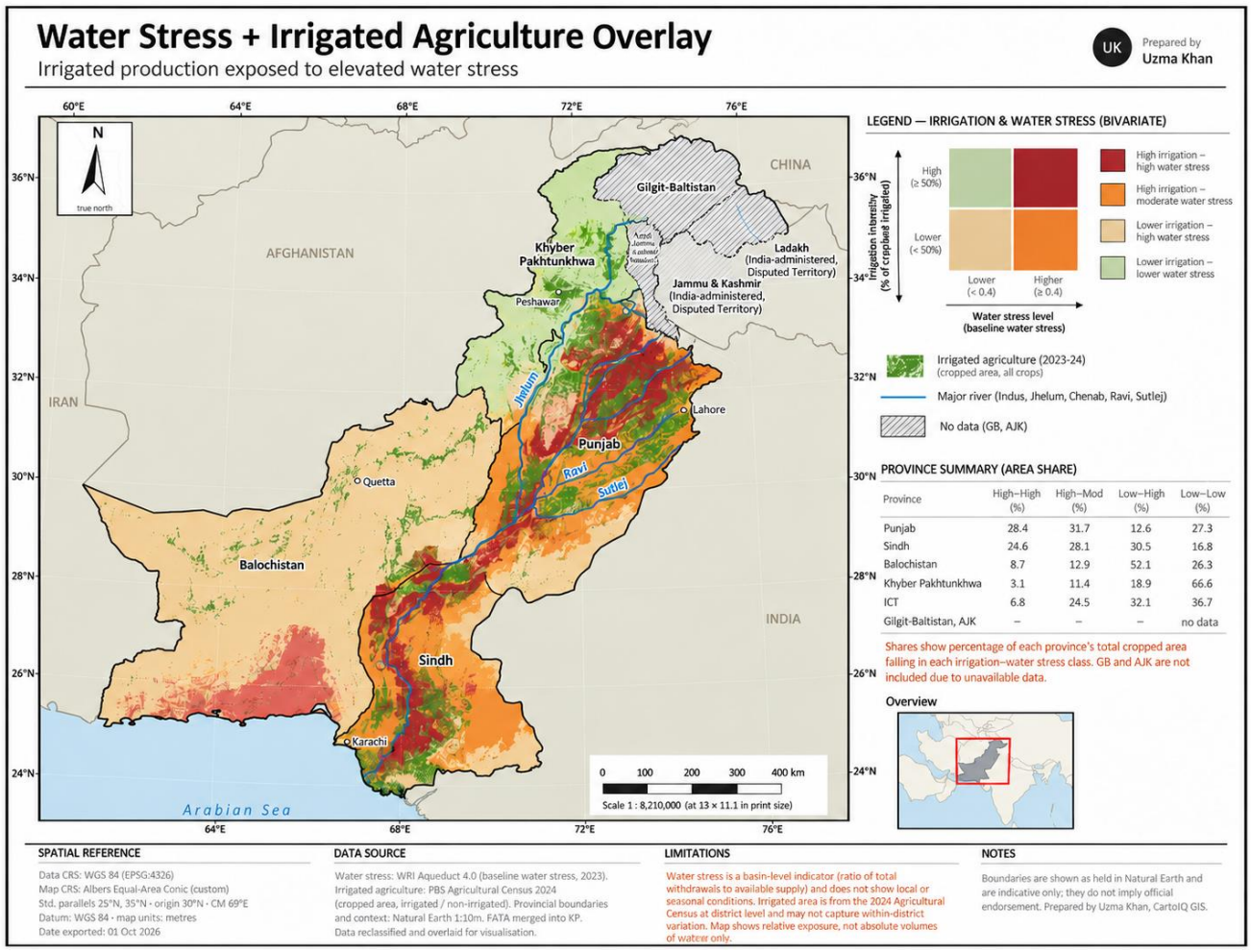


Figure 7.10: Conceptual overlap of irrigated agriculture and baseline water stress.

The conceptual overlap draws attention to irrigated regions potentially exposed to water-resource pressure, but does not establish district-specific stress, crop-level risk or actual water deficits.

Table 7.1. Pakistan relative to the functional comparator panel on selected water and agricultural-productivity indicators.

Indicator	Pakistan	Comparator median	Pakistan / median	Interpretation
Water stress, 2023 (%)	98.1	60.35	1.63x	High pressure relative to comparator panel
Internal renewable water (m3/person)	225.69	699.22	0.32x	Low renewable-water endowment per person
Water productivity (USD/m3)	2.23	11.95	0.19x	Low value generated per unit water
Agricultural value added/worker (USD)	3,185.77	11,387.85	0.28x	Low labor/economic productivity benchmark
Employment in agriculture (%)	36.23	15.76	2.30x	Large labor share remains in agriculture
Irrigated agricultural land (%)	54.17	16.03	3.38x	High irrigation intensity among available observations

The cross-country comparisons in Figure 7.11 show the extent to which water stress and whole-economy water productivity vary across the functional comparator panel. Figure 7.12 places water productivity alongside agricultural value added per worker to examine their descriptive association.

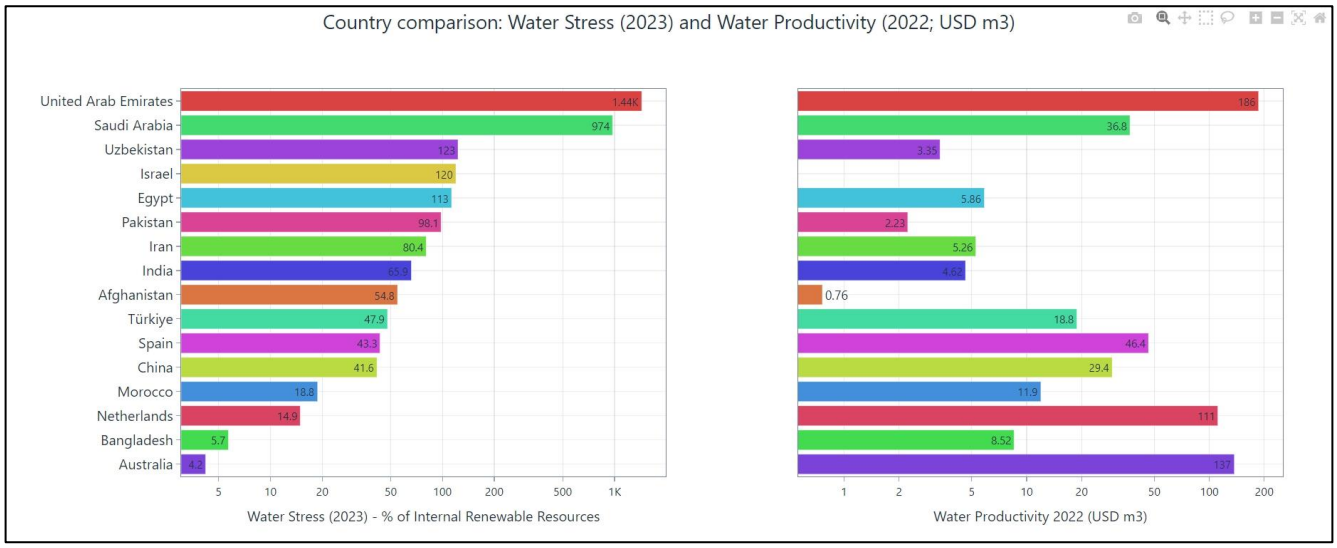


Figure 7.11: Fresh water withdrawals relative to internal renewable water resources ('water stress' in the source chart) and whole-economy water productivity across comparator countries.

Pakistan combines relatively high water stress with low whole-economy water productivity within the selected panel. These are descriptive comparisons and do not establish the causes of observed differences.

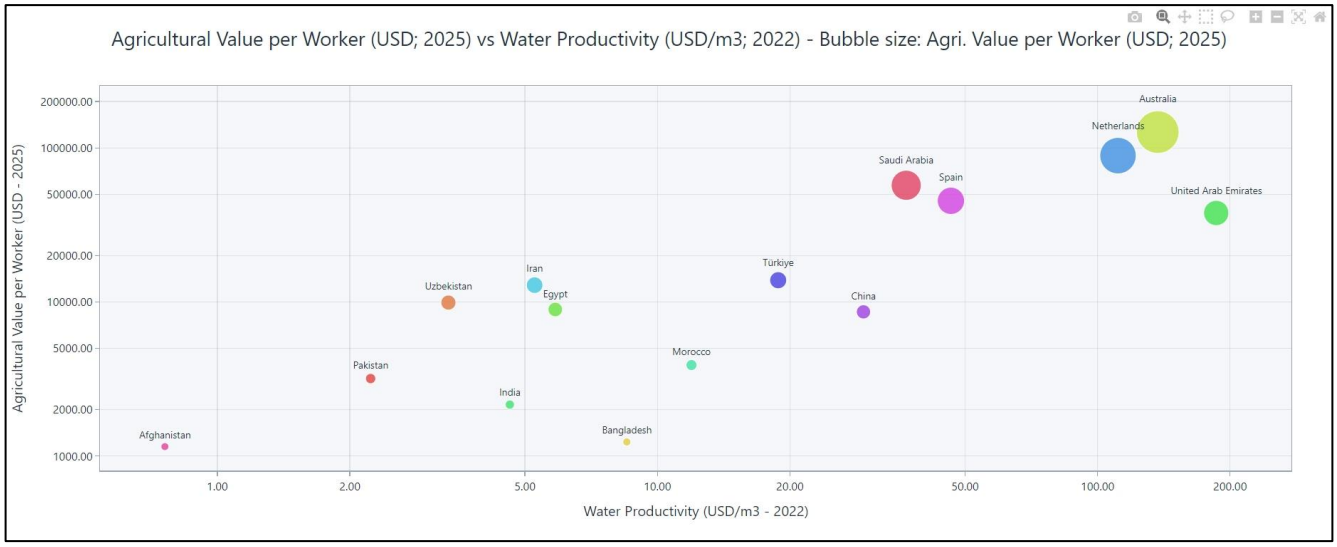


Figure 7.12: Water productivity versus agricultural value added per worker in comparator countries.

Higher water productivity is associated with higher agricultural value added per worker in this sample, but the country-level relationship is not causal and may reflect other economic and structural factors.

8. Agricultural and Food-Production System

8.1 Commodity Canvas

The production database extends wheat, rice, maize, cotton, sugarcane, potato, onion, tomato, mango and citrus. Pakistan's official crop publications cover a much wider set of cereals, pulses, oilseeds, vegetables, fruits and dry fruits. The thesis holds a tiered approach: a deep internationally comparable core, and a broader Pakistan food-system canvas.

Table 8.1: Commodity canvas and principal analytical dimensions.

Group	Examples	Main analytical dimensions
Cereals/staples	Wheat, rice, maize, barley, millet/bajra, sorghum/jowar	Production, yield, food/feed use, trade, volatility
Pulses/protein crops	Gram/chickpea, lentil, mung, mash/urd, peas	Import gaps, protein supply, dryland potential, storage
Oilseeds/edible fats	Rapeseed/mustard, canola, sunflower, soybean, sesame, groundnut, cottonseed; palm/other oils	Import dependence, import substitution, water/land trade-offs, oil quality/storage
Vegetables	Potato, onion, tomato, chillies, garlic, aggregate vegetables	Perishability, storage, seasonal prices, imports/exports, post-harvest loss
Fresh fruits	Mango, citrus/kinnow, banana, dates, apple, guava, grapes, apricot, peach, pear, plum, pomegranate	Yield, export quality, cold chain, coatings/films, processing
Dry fruits/nuts	Almonds, walnuts, pistachios, raisins, dried apricots, figs	Value addition, quality preservation, trade, mycotoxin/moisture risks
Livestock/dairy	Milk, dairy products, beef, mutton/goat meat, poultry, eggs	Nutrition, value added, cold chain, processing and trade
Fisheries	Fish and seafood	Food supply, cold-chain integrity, export value
Other food imports	Tea, sugar and other material food-import categories	Import bill, partner concentration, affordability
Non-food water-using agriculture	Cotton and other major cash crops	Land/water opportunity cost and export-linked value

8.2 Production Quantity versus Nutritional and Economic Contribution

Large tonnage does not necessarily imply high nutritional value, high farm income or efficient water use. The synthesis ombines physical output with producer prices, export unit values, water productivity and food-availability indicators. Milk and livestock are included because a crop-only framework would omit a major part of Pakistan's agricultural economy and dietary supply.

The also treats demand as dynamic. Population growth raises the number of consumers, while income and urbanization can change what those consumers demand. This makes future requirements for edible oils, dairy, animal protein, fruits, vegetables, processed foods, refrigeration and storage potentially different from a simple extrapolation of staple-cereal tonnage.

Water productivity provides a bridge from physical crop output to resource efficiency. Figure 8.1 depicts the spatial concept, complementing the crop-specific yield and trend results that follow in Section 8.3. Its categories are illustrative rather than measured WaPOR extraction results.

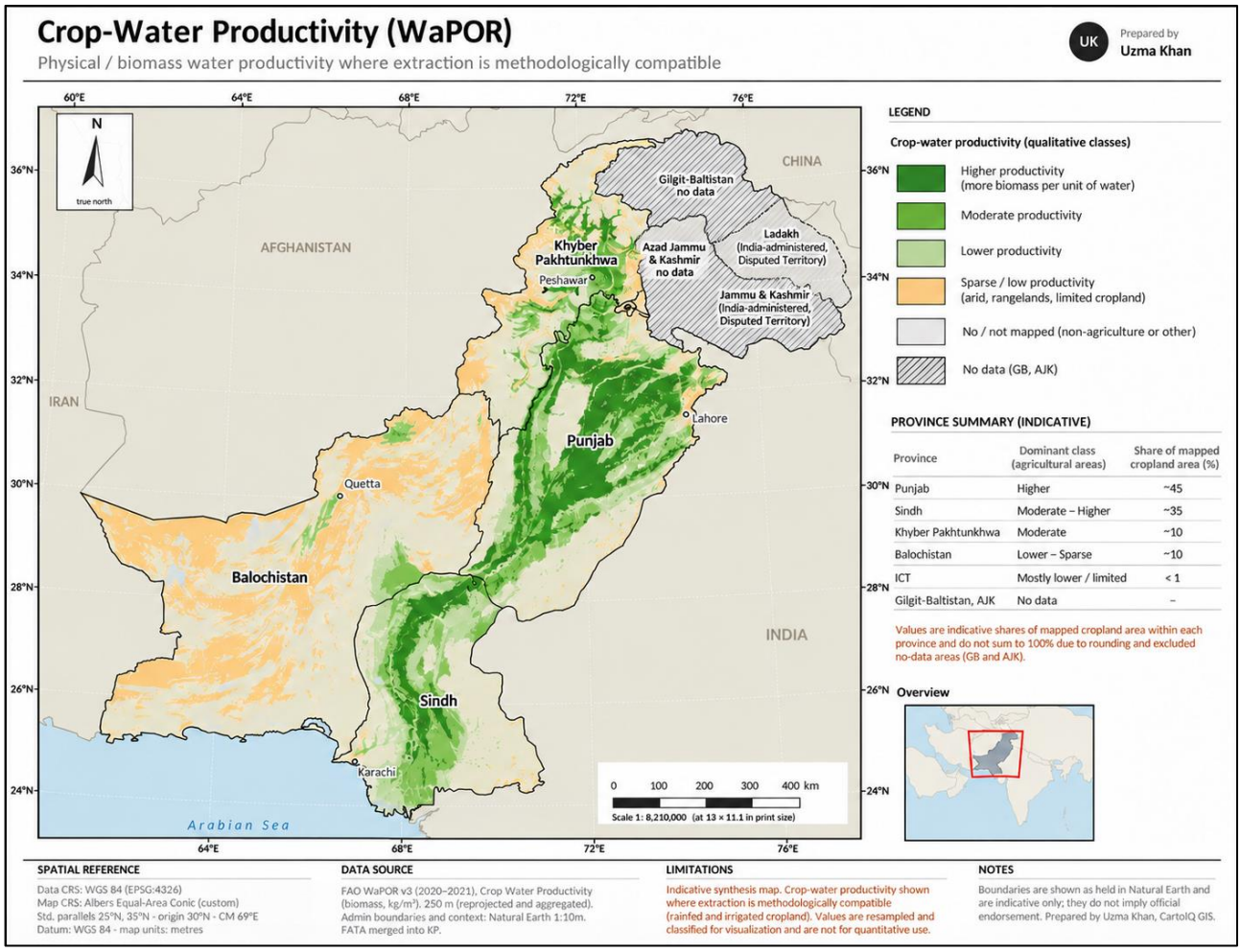


Figure 8.1: Conceptual crop-water-productivity distribution

Higher yields and high biomass production do not necessarily imply higher water productivity, since the water-use denominator can differ across crops, seasons and irrigation systems. Comparable extraction and aggregation are required before regional performance estimates can be reported.

8.3 Major-Crop Production and Yield Results, 2007-2024

The formal crop panel shows broad productivity gains across the six currently harmonized crops. From 2007 to 2024, wheat production increased by about 36.6% and yield by 20.4%; rice production by 81.3% and yield by 28.7%; maize production by 215.3% and yield by 95.4%; sugarcane production by 60.1% and yield by 39.5%; and potato production by 226.7% and yield by 28.7%. Banana is structurally different: production and yield increased strongly while recorded harvested area declined, so endpoint comparisons and the shorter complete series require caution. Formal non-parametric trend tests support positive yield trends for all six crops in the harmonized panel.

Table 8.2: Endpoint changes and non-parametric yield trends for the formal crop panel.

Crop	Production change 2007-2024	Yield change	Sen yield slope / year	Trend p
Wheat	+36.6%	+20.4%	+0.0306 t/ha	<.001
Rice	+81.3%	+28.7%	+0.0248 t/ha	<.001
Maize	+215.3%	+95.4%	+0.1704 t/ha	<.001
Sugarcane	+60.1%	+39.5%	+1.217 t/ha	<.001
Potato	+226.7%	+28.7%	+0.3839 t/ha	<.001
Banana*	+142.4%	+274.8%	+0.4406 t/ha	<.001

The statistical figures in this section move from observed yield trajectories to trend estimates, the separate contributions of area and yield, and structural-break screening. The geographical wheat comparison follows these temporal results so that the spatial and historical evidence is interpreted in sequence.

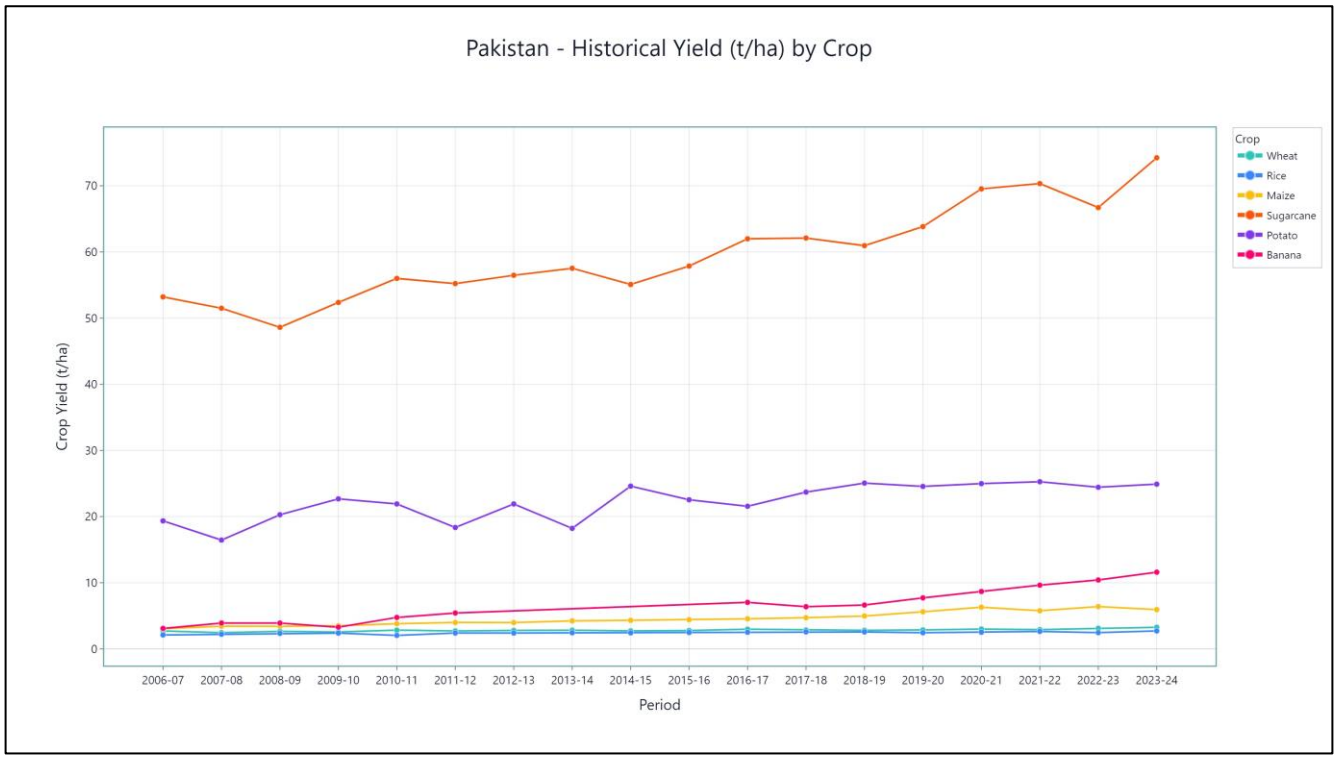


Figure 8.2: Major-crop yield trajectories in Pakistan, 2007-2024.

All six harmonized crop yields show long-run improvement, but their trajectories differ. Indexing highlights relative change without equating the absolute yield scales of crops such as sugarcane and wheat.

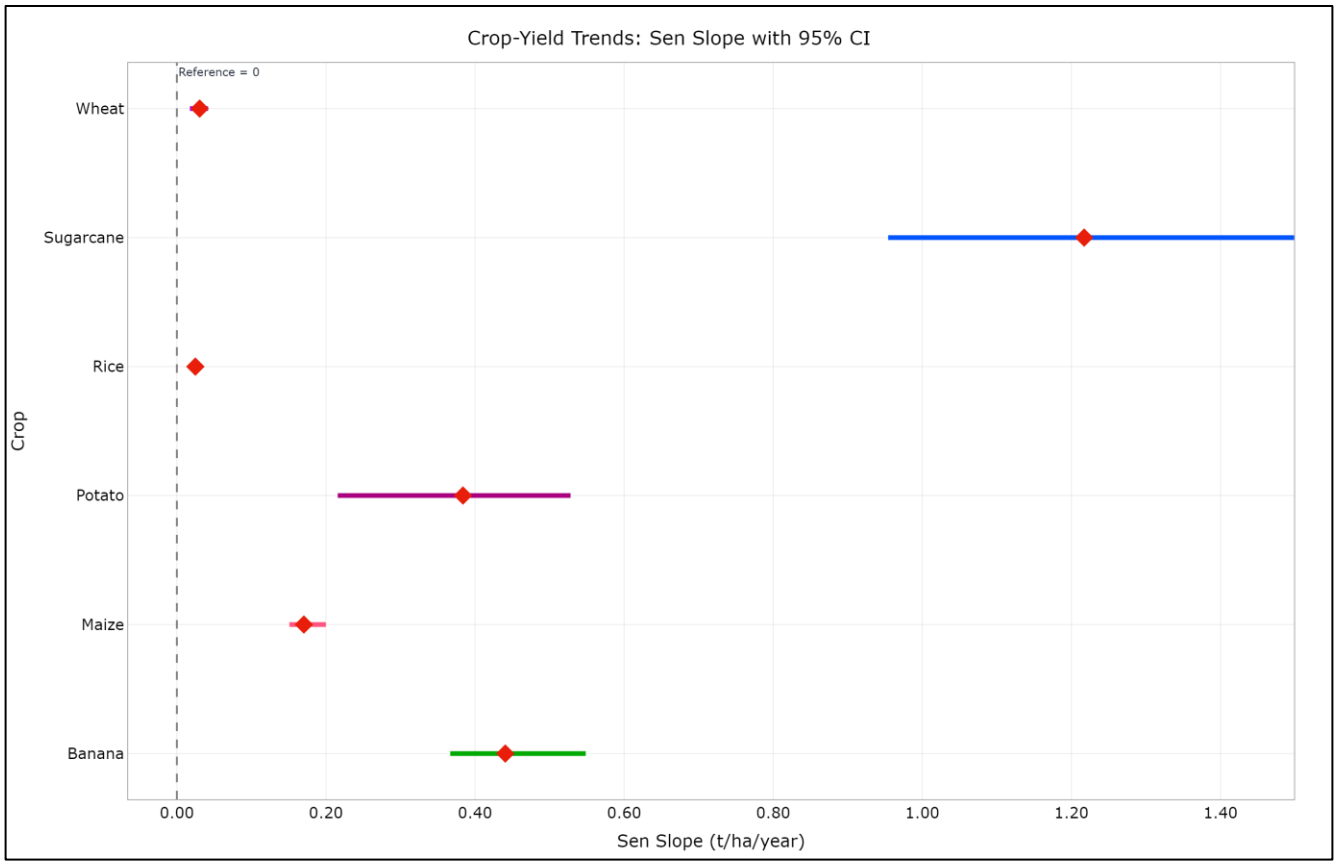


Figure 8.3: Sen-slope estimates and 95% confidence intervals for crop-yield trends.

Verification note: All six Sen slope point estimates reproduce from the annual crop observations where matching year coverage is available; uncertainty intervals retain the originating analysis method and must not be mistaken for independently established source validity.

The available Sen-slope estimates are positive across the six crops, with their reported uncertainty intervals excluding zero. Differences in absolute slopes cannot be interpreted as a cross-crop performance ranking because crop yields have different scales.

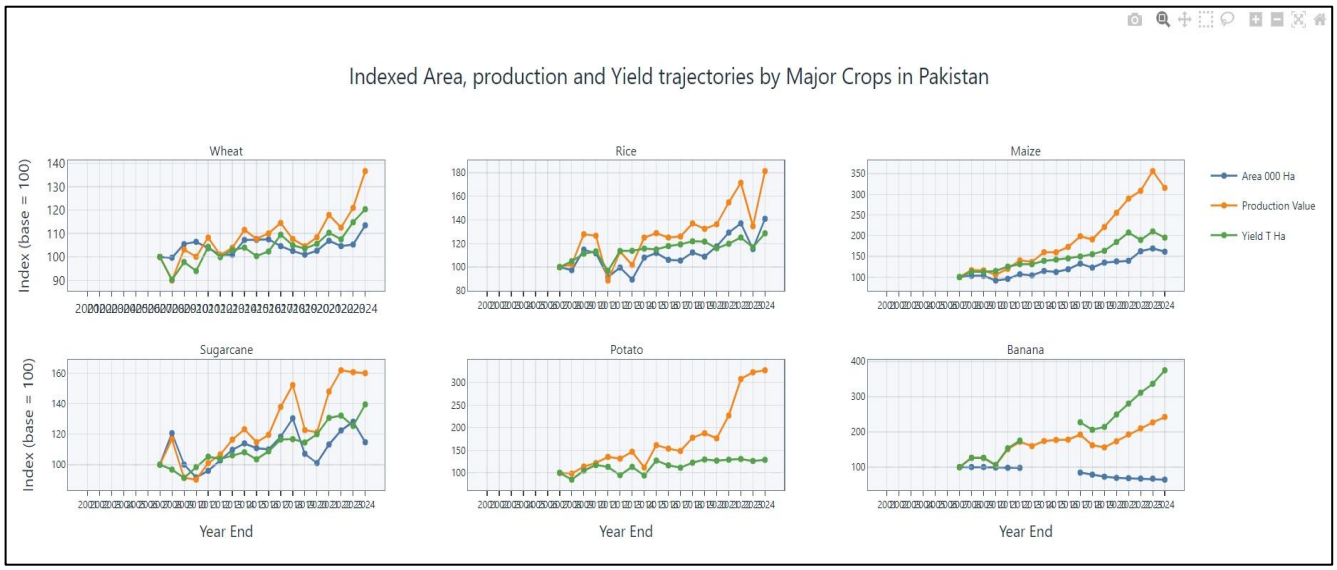


Figure 8.4: Indexed crop area, production and yield by commodity, 2007-2024.

Production gains reflect different combinations of area expansion and yield improvement. This distinction matters economically because expansion can increase land and water requirements even when total production rises.

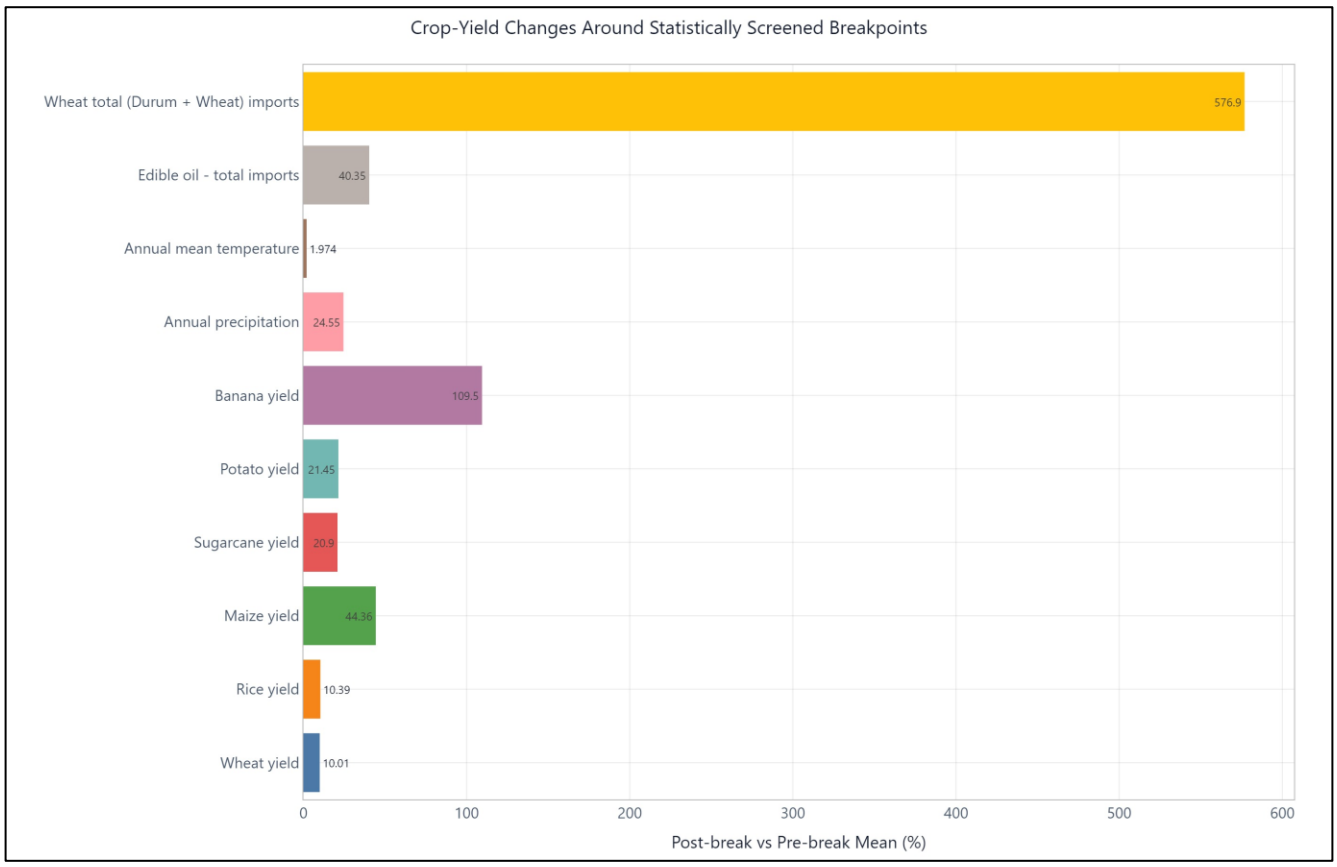


Figure 8.5: Candidate structural changes in crop-yield time series (Pettitt screening).

The candidate breakpoints are statistical screening signals, not evidence that any particular policy, cultivar or irrigation intervention caused a change. Their value lies in identifying periods for subsequent investigation.

Figure 8.6 places wheat yield beside irrigation dependence at the provincial scale. The comparison is a spatial complement to the crop-panel results: it describes co-occurrence, not the yield response that would follow from additional irrigation.

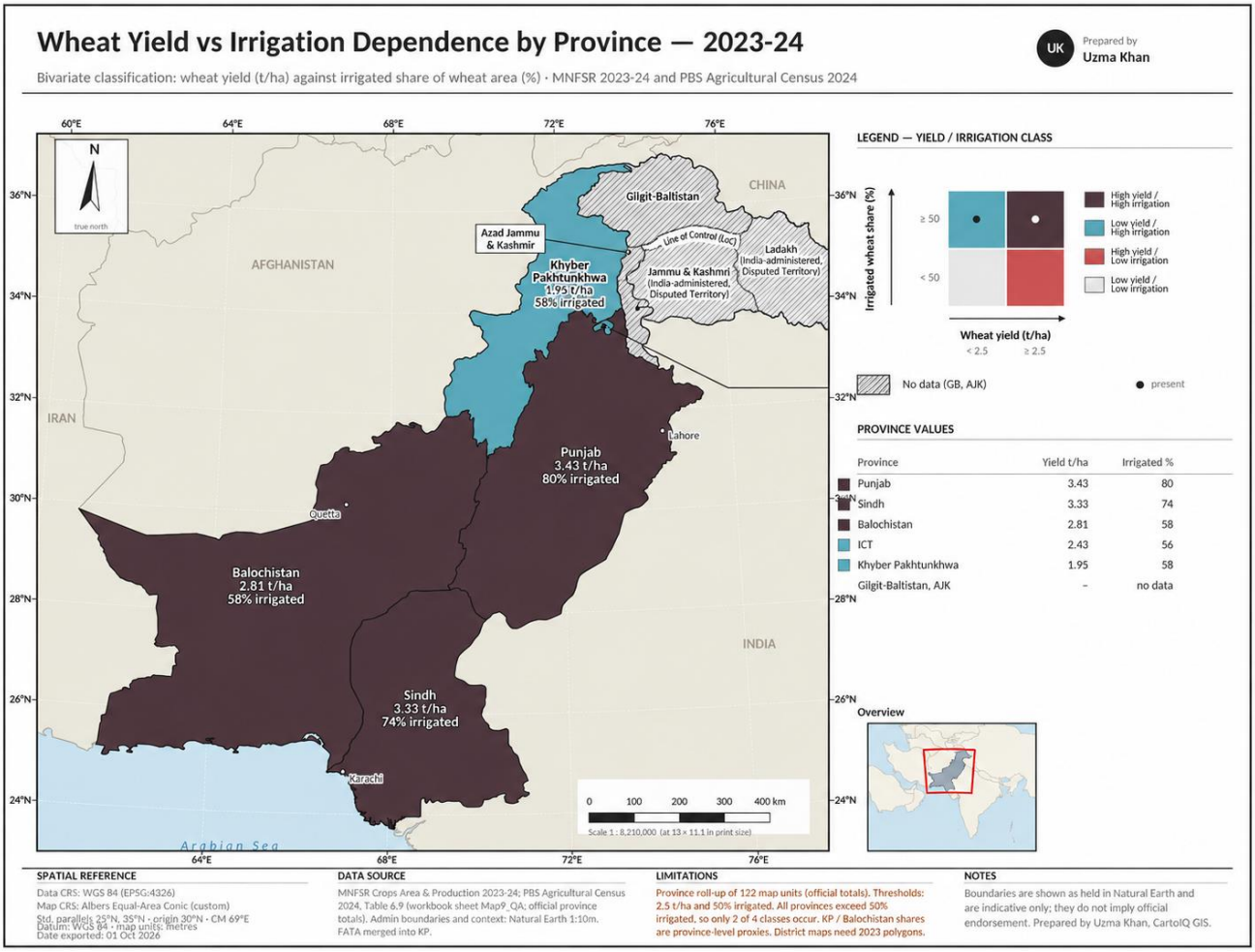


Figure 8.6: Provincial wheat yield and irrigated wheat-area share, 2023-2024.

Punjab and Sindh combine comparatively high wheat yield and irrigated share in the provincial observations. The relationship is descriptive; it does not control for soil, variety, fertilizer, climate or within-province differences.

Production and water inputs must also be evaluated in terms of the food and resource value retained after harvest. Figure 8.7 introduces the spatial food-loss and embedded-water concept, linking the agricultural-production evidence in this chapter to the preservation and value-chain analyses elsewhere in the synthesis.

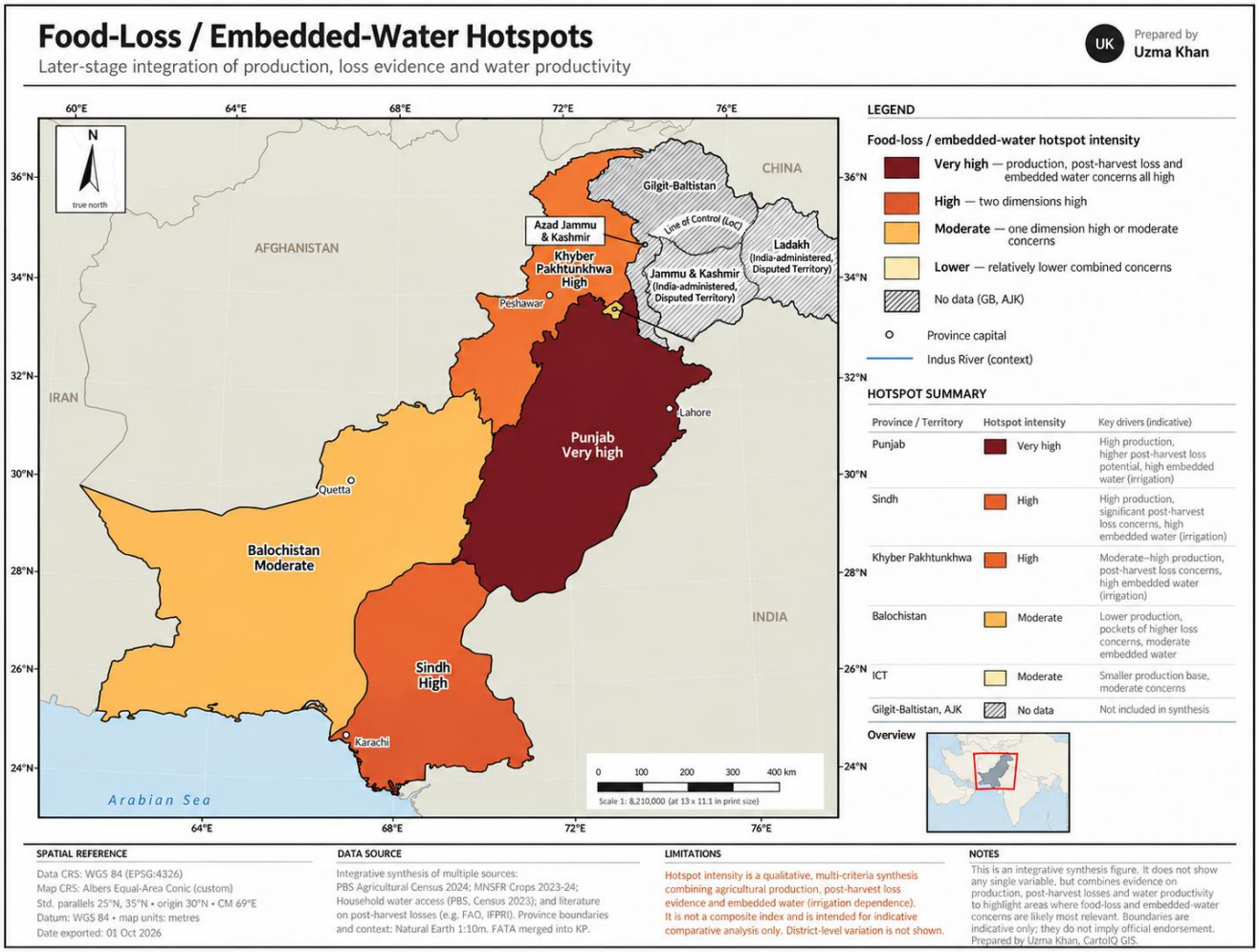


Figure 8.7: Conceptual food-loss and embedded-water concern areas (GIS M10; illustrative).

The hotspot figure is a research framework for identifying locations requiring matched commodity-level production, loss and water-use evidence. Its colored categories are not observed or validated hotspot scores.

8.4 Crop Genetic Improvement, Biotechnology and Advanced Breeding

The innovation evidence needs to be interpreted as a maturity pipeline rather than a single biotechnology score. Pakistan has established commercial GM cotton, while several NIGAB/PARC programs in wheat, potato, tomato, groundnut and other crops remain at research or regulatory-pipeline stages. Banana tissue culture is already commercialized and has been used to distribute virus-free planting material; zinc-biofortified wheat is a scaled non-GM breeding and seed-system intervention; and recent mango phenotypic and molecular-diversity studies expand the breeding base without constituting commercial GM mango. Internationally, India provides a nearby genome-editing comparison, Australia provides a disease-resistant GM banana regulatory case, the Americas represent mature commercial biotechnology systems, and the European Union provides a distinct new-genomic-technique regulatory pathway. The comparison is therefore technology-specific rather than a simple country ranking.

Table 8.3: Current crop-genetics and biotechnology evidence streams in Pakistan.

Evidence stream	Pakistan status	Example / evidence	Interpretive status
Commercial GM crop	Established	Bt/stacked-trait cotton approvals and commercial seed use	Commercial practice; adoption needs to be reported separately from approval
Genome editing / CRISPR	Research pipeline	Potato browning; wheat yield/root architecture and related projects	Research/development; do not describe as commercial adoption
Biofortification	Scaled	Zinc-biofortified wheat seed system	Non-GM breeding; nutrition-oriented deployment
Tissue culture	Commercialized	Virus-free banana planting material; NIGAB-1 and NIGAB-2	Scaled biotechnology, not genetic engineering
Mango genetic improvement	Pre-breeding / molecular characterization	Phenotypic diversity and SSR-based diversity studies	Breeding resource; not commercial GM mango

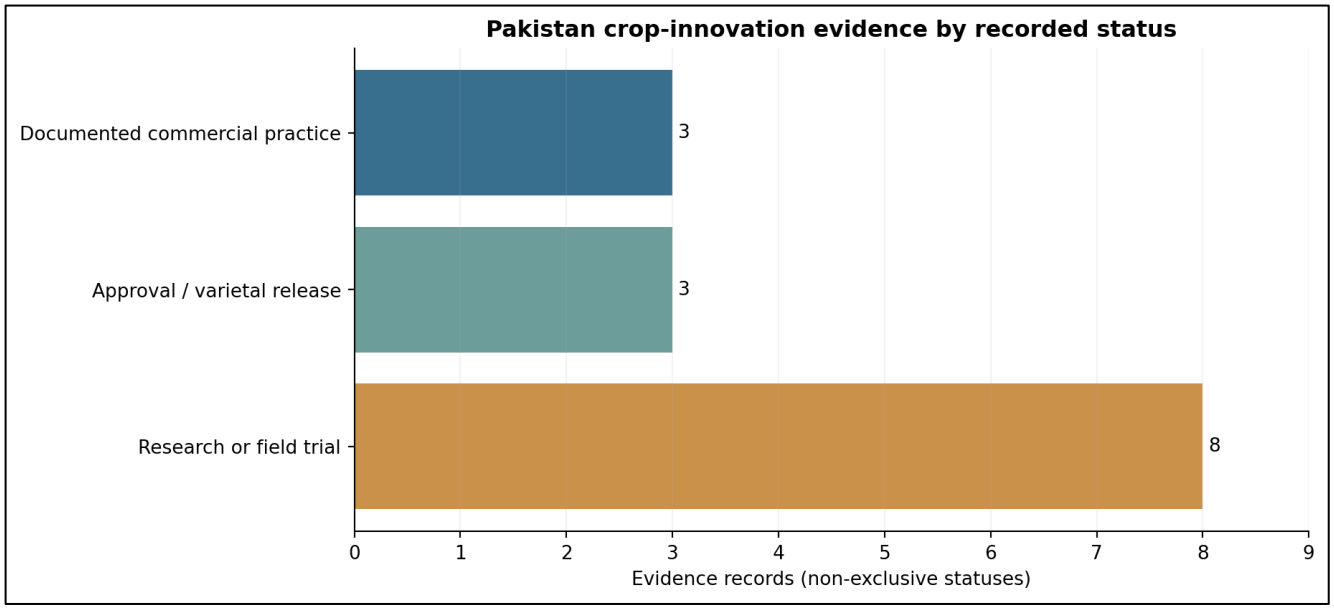


Figure 8.8: Pakistan crop-innovation maturity across breeding and biotechnology pathways.

Evidence boundary: *Binary research, approval and practice flags are non-exclusive classification records, not measured adoption rates or shares. Dated regulatory and deployment documents remain essential for external verification.*

The technologies occupy different development stages, from commercial practices to research and regulatory pipelines. Their maturity require separate evaluation rather than condensed into one innovation score.

The international comparison is technology-specific: commercial adoption, regulatory approval and research capability represent different outcomes and cannot be treated as equivalent.

International Crop-Biotechnology Benchmark by Technology Type and Maturity/Status

Country / region	Commercial GM	Genome-edited release/approval	Advanced breeding R&D	Scaled biofort./tissue culture
Pakistan	Yes	No	Yes	Yes
India	Yes	Yes	Yes	No
Australia	Yes	R/F	Yes	No
United States	Yes	No	Yes	No
Brazil	Yes	No	Yes	No
Canada	Yes	No	Yes	No
Argentina	Yes	No	Yes	No
European Union	R/F	R/F	Yes	R/F
Italy	No	R/F	Yes	No
France	No	R/F	Yes	No
Netherlands	No	R/F	Yes	No

Yes = documented commercial/scaled practice; R/F = research or regulatory/framework stage; No = no commercial claim in reviewed evidence

Figure 8.9: International biotechnology comparison by technology and maturity.

8.5 Representative Crop/farm Economics Screening

The farm-economics assessment applies a common 100-ha analytical scale to the six harmonized crops so that price, production cost, post-harvest loss, yield and water-use assumptions can be compared consistently. The exercise is an evidence-based screening layer rather than a nationally representative farm survey. Yield observations are tied to the completed crop panel, while prices, costs, water requirements and loss rates use the best available regional, study-specific or proxy evidence documented in the companion economics input/evidence register. Differences in geography, farm system, source year, market level and accounting boundary therefore remain material. Results needs to be interpreted as conditional cases and sensitivity-tested rather than generalized to all producers.

Evidence classification: This analysis combines observed historical crop yields with indicative farm-gate prices, production-cost proxies, post-harvest loss factors and assumed water requirements. The common 100-ha scale is a normalization device, not a sample of actual farms. Economic results are conditional calculations under specified inputs; they are not externally validated estimates of Pakistan farm profitability, and the absence of matched farm-level records prevents a defensible national ranking. The analysis nevertheless identifies decision thresholds and the variables to prioritize in future field validation.

Table 8.4: Representative six-crop farm-economics screening results (100-ha analytical cases).

Crop	Gross revenue	Total cost	Net return	BCR	Yield / break-even (t/ha)	Screening interpretation
Banana	$102.1k	$257.1k	-$155.0k	0.40	11.60 / 29.20	Strongly negative under current regional/proxy inputs; price/cost basis and high loss rate require sensitivity testing.
Maize	$97.3k	$21.6k	+$75.7k	4.50	5.93 / 1.32	Strongly positive screening result; unusually low regional cost basis makes cost sensitivity essential.
Potato	$277.4k	$52.4k	+$225.0k	5.29	24.90 / 4.70	Strongly positive screening result; cost and price source vintages differ, so profitability cannot be treated as a current national estimate.

Crop	Gross revenue	Total cost	Net return	BCR	Yield / break-even (t/ha)	Screening interpretation
Rice	$75.9k	$76.1k	-$0.3k	1.00	2.71 / 2.72	Approximately break-even; small changes in price, cost, loss or yield can reverse the sign.
Sugarcane	$224.9k	$214.0k	+$10.9k	1.05	74.24 / 70.66	Marginally positive; fixed/variable cost split includes an inferred component and needs to be treated as screening evidence.
Wheat	$88.5k	$91.1k	-$2.6k	0.97	3.27 / 3.36	Slightly below break-even; close enough that plausible price/cost/yield changes can materially alter the result.

Source / preparation note: Crop and farm economics assessmentcarried out in Brill-Viz. Monetary values are pre-tax, single-period screening outputs on a 100-ha analytical scale. BCR = gross revenue / total cost. Inputs are representative regional/proxy values documented in the companion farm-evidence register; they are not a nationally representative Pakistan farm budget.

The ranking is intentionally not converted into a claim that one crop is intrinsically 'better' than another. Maize and potato appear highly profitable under the current base inputs, but those outcomes are especially sensitive to the production-cost evidence used. Rice, wheat and sugarcane lie close to break-even, making them useful examples of how modest changes in prices, costs, losses or yield can change farm viability. Banana is substantially negative in the current case, with realized yield far below the modeled break-even yield; this needs to be read as a warning about the joint input assumptions rather than as a national conclusion about banana farming.

Water-productivity reporting requires one additional guardrail. The current farm-economics assessment labels a metric as 'physical water productivity (kg/m3)' but calculates marketed output after post-harvest loss divided by the water-use proxy. For the synthesis, physical crop-water productivity is defined consistently as harvested yield (kg/ha) divided by water use (m3/ha). On that basis, the corresponding screening values are approximately 0.682 for banana, 0.913 for maize, 4.150 for potato, 0.471 for rice, 3.712 for sugarcane and 0.594 kg/m3 for wheat. If marketed output is used instead, it needs to be labelled explicitly as marketed-food output per withdrawn cubic metre. These water values are seasonal crop-water-use proxies rather than measured farm withdrawals or consumptive-use observations.

8.6 Economics Interpretation, Decision Thresholds and Underlying Chart Evidence

The representative 100-ha crop cases use regional or proxy input evidence. Net farm return is gross saleable revenue less allocated operating and other project costs; benefit-cost ratio is gross revenue divided by total cost. Break-even output estimates are scenario-specific, and the ranking of crops must not be interpreted as nationally representative profitability. The corresponding Brill-Viz source reports also supply farm-production/retention, revenue and operating margin, gross-revenue/cost/net-return, and yield/break-even charts for each of the six commodities.

Robustness priority: Maize and potato positive margins are particularly dependent on cost and price assumptions; cases near break-even may change sign under modest input changes. The appropriate interpretation is comparative input sensitivity, not demonstrated crop-level superiority. The minimum validation dataset comprises same-location, same-season farm-gate price, harvested and marketed yield, itemized input and labour costs, irrigation withdrawals or consumptive use (clearly distinguished), land costs and observed losses.

Table 8.5: Farm-screening sensitivity and interpretation register (six crops).

Crop	Reported net return / 100 ha	Primary uncertainty / decision implication
Banana	−US$155.0k	Check price, cost basis and high post-harvest losses before extrapolation.
Maize	+US$75.7k	Low assumed costs: test regional input costs and price downside.
Potato	+US$225.0k	Different price/cost source vintages: harmonization essential.
Rice	−US$0.3k	Near break-even; small changes can reverse investment outcome.
Sugarcane	+US$10.9k	Marginal result; audit estimated fixed/variable cost allocation.
Wheat	−US$2.6k	Near break-even; test farmgate prices, yield and loss assumptions.

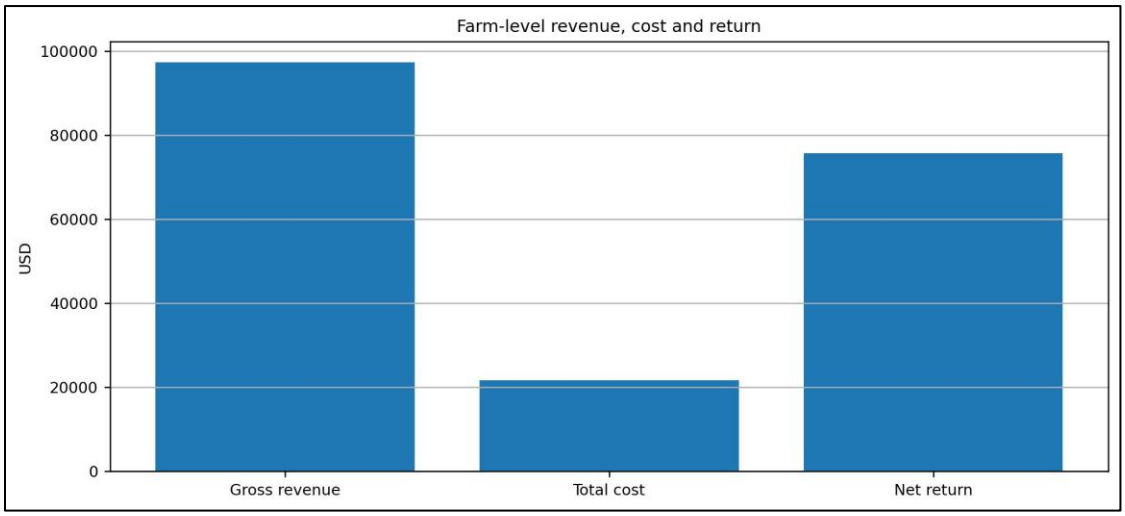


Figure 8.10: Brill-Viz 100-ha maize farm screening: revenue, costs and net return (illustrative; not nationally representative).

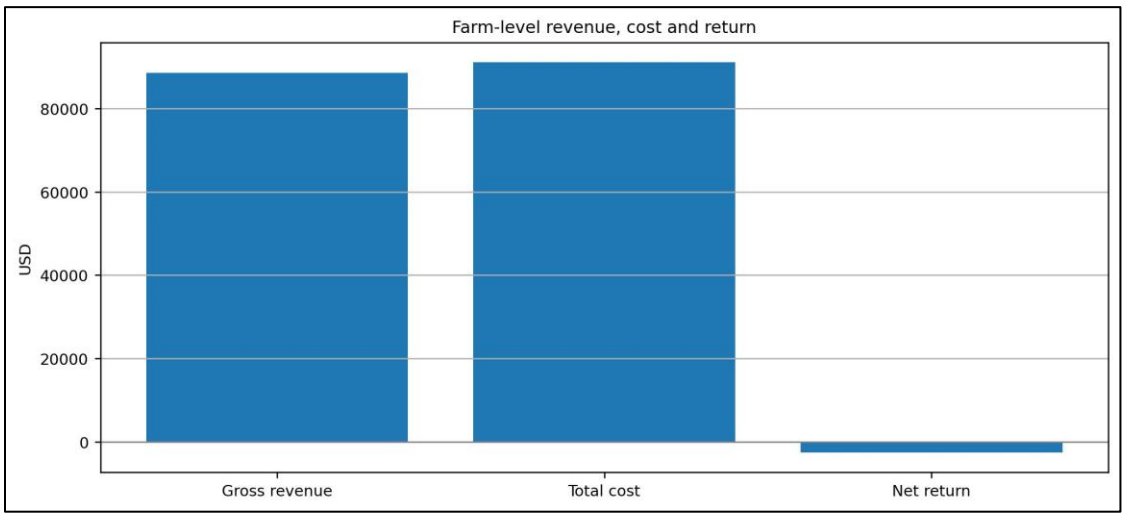


Figure 8.11: Brill-Viz 100-ha wheat farm screening: revenue, costs and net return (illustrative; not nationally representative).

9. Food Trade, External Balance and Economic Security

The trade module treats imports and exports as integral components of food security and macroeconomic performance. Import dependence can be beneficial when imports use less scarce domestic water than local production would require, but it can create exposure to exchange rates, shipping disruptions, geopolitical concentration and international prices. Export expansion can improve foreign exchange and value addition, but it requires evaluation against domestic availability and water opportunity cost.

Table 9.1: Core food-trade and economic-security metrics.

Metric	Definition	Interpretation
Import dependency ratio	Imports / apparent domestic supply	Exposure of domestic supply to imports
Self-sufficiency ratio	Domestic production / apparent domestic supply	Domestic supply capacity
Net food/agri trade value	Exports - imports	Foreign-exchange contribution or burden
Import-bill share	Commodity import value / total food import value	Identifies major import-pressure commodities
Export-earnings share	Commodity export value / total food/agri exports	Identifies foreign-exchange earning commodities
Unit value	Trade value / quantity	Approximate value/quality/price movement; not identical to farm-gate price
Partner concentration	Herfindahl-Hirschman index of partner shares	Supply or market concentration risk
Economic water productivity	Gross value / consumptive water use	Value obtained from scarce water
Virtual/embedded water perspective	Water embodied in production/trade, where defensibly estimated	Connects trade decisions to water scarcity

Import-substitution scenarios do not assume that every imported food needs to be produced domestically. A substitution option is considered attractive only if agronomically feasible and compatible with land, water, climate, cost and food-security constraints. The same logic applies to export expansion.

9.1 Current Trade and Real-Price Evidence

The strongest completed trade signal is the long-run rise in edible-oil imports. For 2006-2024, total edible-oil import quantity has a strong positive Kendall trend (tau about 0.74, $p < .001$), with a Sen slope of roughly 91 thousand tonnes per year; nominal import value rises even more strongly. Palm oil drives much of that pattern. Wheat imports behave differently: the 2007-2024 import-quantity series does not show a significant monotonic trend, consistent with episodic policy, stock and domestic-supply responses. Real wheat support and wholesale prices also do not show simple monotonic 2005/2007-2024 trends, although wheat imports are positively associated with contemporaneous real wholesale prices in the present observational sample. These relationships require deeper economics before they can support policy conclusions.

Table 9.2: Selected completed trade and real-price trend evidence.

Series	Window	Kendall tau	Sen slope	Interpretation
Edible-oil import quantity	2006-2024	0.743	+91.3 thousand t/year	Strong positive long-run import trend
Edible-oil import value (nominal)	2006-2024	0.883	+PKR 24,373 million/year	Strong nominal import-bill growth
Palm-oil import quantity	2006-2024	0.836	+93.5 thousand t/year	Major contributor to edible-oil trend
Wheat import quantity	2007-2024	0.034	Not material	No monotonic long-run trend; episodic imports
Real wheat support price	2005-2024	Not significant	-	No robust monotonic trend in real terms

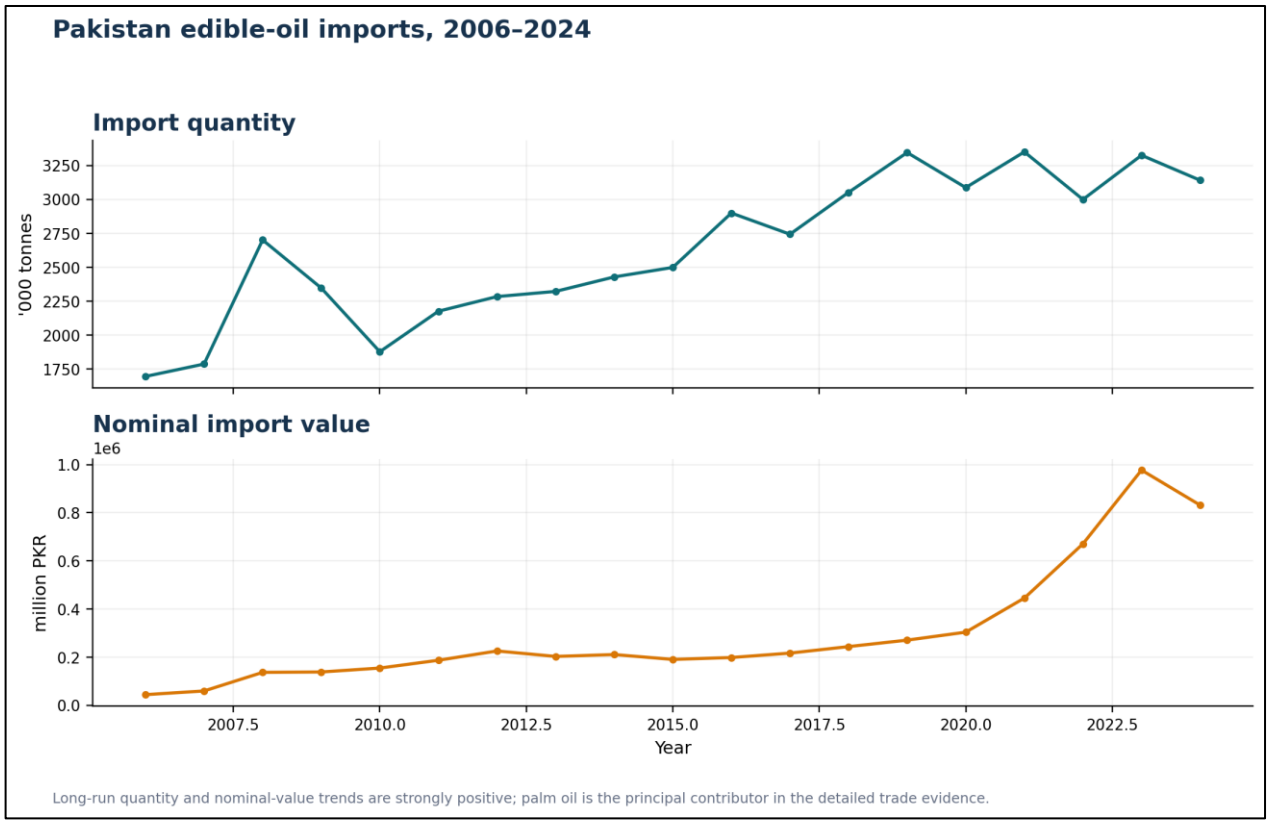


Figure 9.1: Pakistan edible-oil import quantity and value, 2006-2024.

Interpretation: *Edible-oil imports show one of the clearest long-run external-exposure signals in the study. Import quantity rises strongly and nominal import value rises even faster; detailed evidence indicates that palm oil accounts for much of the increase.*

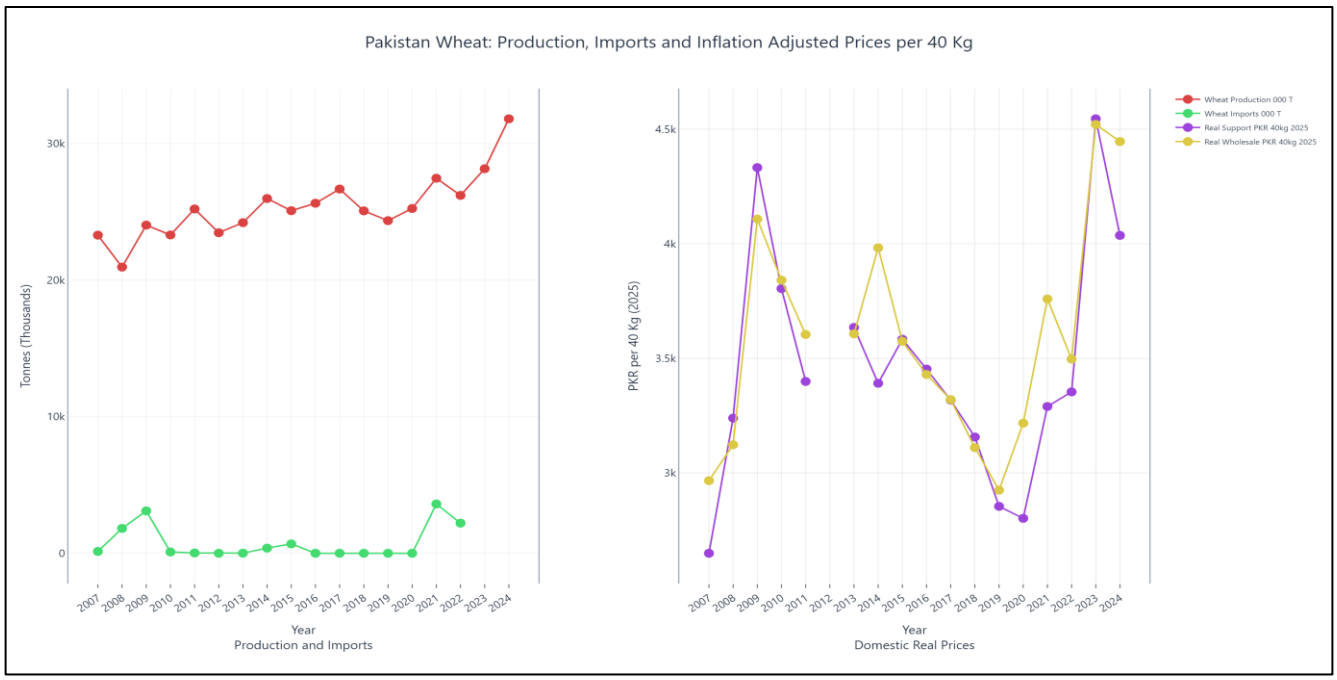


Figure 9.2: Pakistan wheat imports, domestic production and real domestic wheat prices.

Interpretation: *Wheat differs from edible oil: imports are episodic, not a stable upward monotonic trend, and domestic production has continued to rise. Real support and wholesale prices also do not show simple monotonic trends, so policy conclusions require event-specific and econometric analysis rather than trend extrapolation.*

9.2 Economic Transmission from Production to Food Security

The principal transmission mechanisms examined in this study are (a) seasonal weather and water availability to crop output, (b) irrigation and input costs to producer margins, (c) post-harvest losses and storage costs to marketable supply, (d) domestic output, food imports and exports to trade exposure, and (e) energy prices and exchange rates to the cost of food production, transport and imports. These channels are analytically linked but must not be interpreted as proven causal mechanisms unless an identification design and suitable observations support that inference.

The proposed descriptive indicators are food-import value as a share of merchandise imports; the relevant food-import basket as a share of GDP; net food-trade balance; food-import bills relative to international reserves (with matched or flagged observation years); and domestic production per person. Country-level gaps in exact commodity HS codes, mismatched vintages or the absence of Pakistan-specific import components must be disclosed for each calculation. No national import-exposure coefficient is estimated solely from the global 2024 snapshot.

The completed financial-trade dataset materially strengthens the external-security chapter. Across 211 country/area rows, GDP is now populated for 204, merchandise imports and exports for 199, fuel-import and fuel-export shares for about 194 and 193, reserves for 180 and current-account balance for 196. These fields allow the synthesis to separate the physical food trade problem from the wider macroeconomic capacity to pay for food, fertilizer, energy, machinery and cold-chain inputs.

For Pakistan, the latest completed dataset reports merchandise imports of about US$65.85 billion and exports of about US$30.55 billion, a merchandise deficit near US$35.3 billion. Applying the latest World Bank fuel-import share to the merchandise import bill gives a broad fuel-import proxy of about US$20.8 billion, equivalent to roughly 5.1% of GDP; the net fuel-import pressure proxy is about 5.0% of GDP. This is a near-year proxy based on merchandise trade and fuel shares, not an exact oil/gas customs bill. Pakistan's available exact-HS hydrocarbon total remains explicitly partial, so it is not used as a comprehensive national energy-import figure.

Table 9.3: Pakistan macro-financial and energy-exposure context relative to the core comparator panel.

Indicator	Pakistan	Core comparator median	Interpretive note
Merchandise imports (US$ bn)	65.85	254.06	Latest available; scale differs greatly across countries
Merchandise exports (US$ bn)	30.55	273.36	Latest available; not a performance ranking
Merchandise trade balance (US$ bn)	-35.30	-18.10	Negative = merchandise deficit
Fuel import bill proxy (US$ bn)	20.76	17.51	Broad merchandise x fuel-share proxy
Fuel import bill proxy (% GDP)	5.10%	3.18%	Gross fuel-import pressure
Fuel net-import pressure proxy (% GDP)	4.97%	1.42%	Import proxy minus export proxy, floored at zero
Current-account balance (% GDP proxy)	-0.11%	-0.81%	Latest/aligned or near-year country values
Combined oil/gas domestic coverage	51.1%	54.9%	Physical energy coverage; latest available

Note. Comparator medians exclude Pakistan and use available values for the 15-country functional comparator panel. Fuel-dollar indicators are broad WDI/WTO-derived proxies and does not represent exact crude-oil/LNG customs bills. Observation years vary and are identified in the indicator-level source records.

The food-system relevance is operational: imported energy can affect irrigation pumping, mechanized field operations, fertilizer and chemical costs, trucking, refrigeration, processing and the economics of post-harvest investment. The analysis therefore uses gross fuel import exposure together with export earnings, net-import pressure, current-account context and domestic oil/gas coverage, rather than interpreting one large import bill as vulnerability by itself.

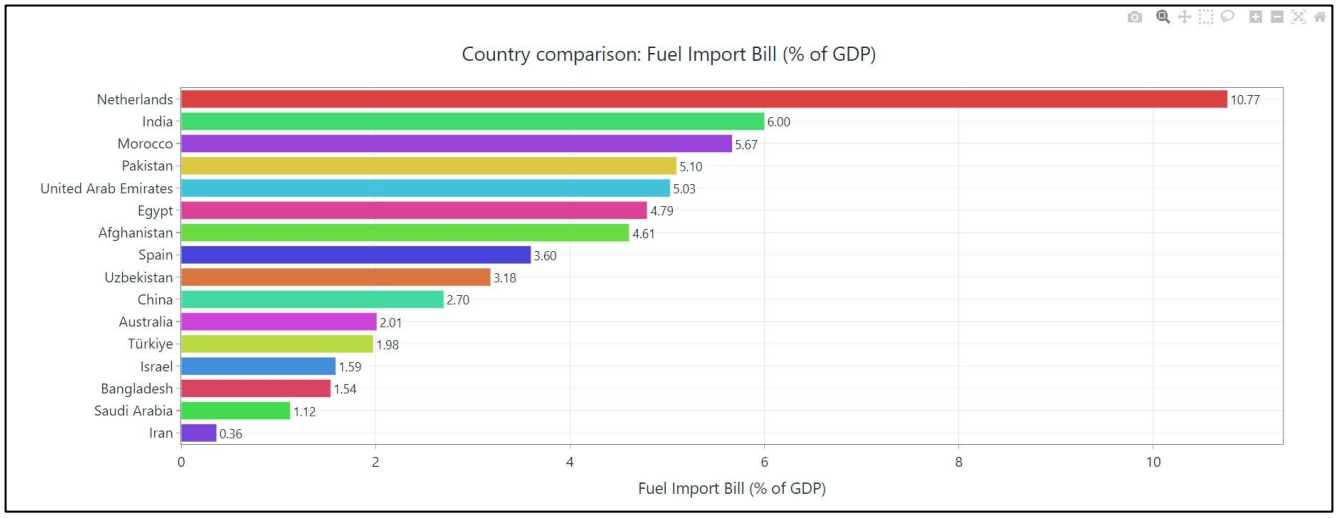


Figure 9.3: Fuel import bill pressure across functional comparator countries.

Evidence boundary: *The fuel-import indicator is a mixed-year proxy expressed relative to GDP; it is not a harmonized official fuel-import account or a precise rank of national exposure.*

Interpretation: *Pakistan's gross fuel-import pressure is above the median of the functional comparator panel, but gross imports alone are not a vulnerability ranking. The Netherlands, for example, combines very high fuel imports with a major trade/logistics role and substantial fuel exports. Net pressure, export reliance and current-account context are therefore needed before interpreting exposure.*

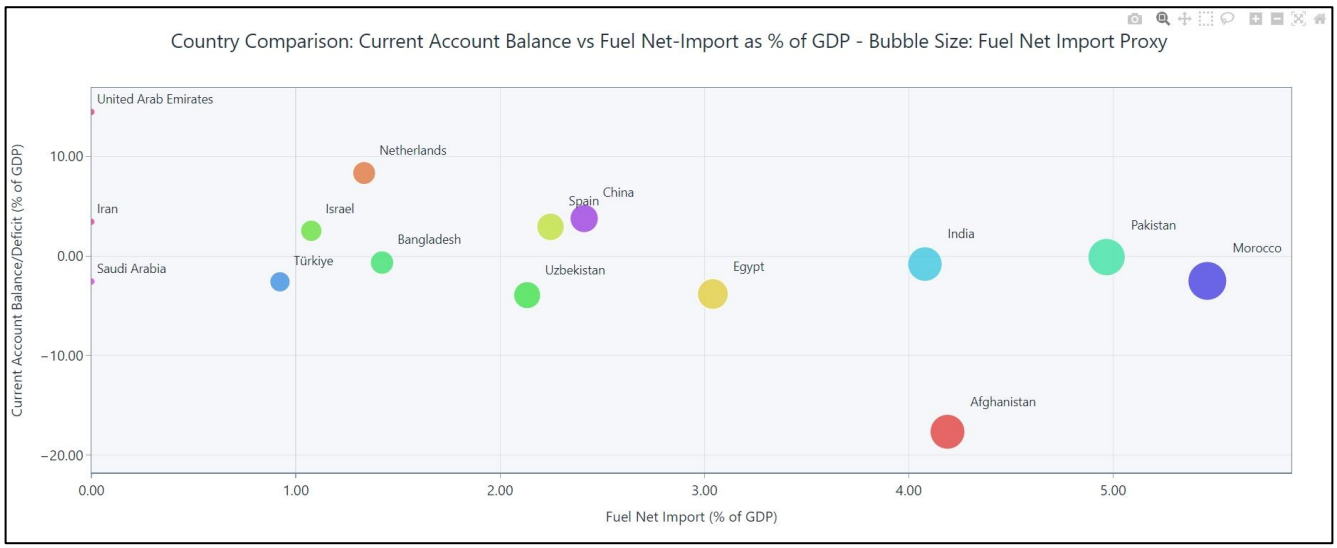


Figure 9.4: Fuel net-import pressure and current-account context across functional comparators.

Interpretation: *Similar levels of fuel-import pressure can sit beside very different external balances because exports, services, remittances, investment income and other macroeconomic flows differ. Pakistan lies close to current-account balance in the latest observation while carrying a comparatively high fuel net-import pressure proxy. The figure is, therefore, a context map, not evidence that fuel imports caused the current-account position.*

9.3 Observed Agricultural-Trade Economics Completed for This Synthesis

The economics layer is now sufficiently developed to distinguish three types of evidence: observed historical outcomes, econometric trend estimates and illustrative investment scenarios. The observed trade series show that total edible-oil imports increased from about 1.696 million tonnes in 2005-06 to 3.140 million tonnes in 2023-24, an increase of about 85.2%. Over the same endpoints, the nominal import bill increased from about PKR 44.2 billion to PKR 831.7 billion. A log-linear HAC trend model estimates average import-quantity growth of about 3.38% per year and nominal import-bill growth of about 13.48% per year. These are historical associations; the nominal-value trend combines quantity, world-price, product-mix, inflation and exchange-rate effects.

A symmetric accounting decomposition of the increase in the edible-oil bill attributes approximately PKR 210.1 billion (26.7%) of the PKR 787.5 billion nominal increase to the change in physical quantity and approximately PKR 577.3 billion (73.3%) to the change in nominal unit value. This decomposition reconciles the accounting identity but cannot be interpreted as a causal attribution to any single price or exchange-rate mechanism.

The 2024 BACI food-and-agriculture aggregate provides a complementary calendar-year trade view. In the BACI sector aggregation adopted for this analysis, Pakistan records approximately US$8.63 billion of food-and-agriculture exports and US$8.46 billion of imports, a small positive balance of about US$0.175 billion. These BACI aggregates are useful for international partner and flow analysis but are not directly interchangeable with Pakistan Bureau of Statistics fiscal-year trade accounts. Indonesia is the largest food-and-agriculture import partner in the 2024 BACI trade aggregation, accounting for about 31.8% of the import-direction total, which makes partner concentration a relevant resilience consideration.

Table 9.4. Completed observed economics and external-exposure results used in the synthesis.

Indicator	Completed result	Interpretation
Edible-oil import quantity	1.696 Mt (2005-06) -> 3.140 Mt (2023-24); +85.2%	Physical import requirement increased materially.
Edible-oil quantity trend	+3.38% per year; HAC log-linear model	Historical trend, not a causal demand model.
Edible-oil nominal import bill	PKR 44.2 bn -> PKR 831.7 bn; +1,781%	Nominal values include quantity, price and FX effects.
Nominal bill decomposition	26.7% quantity contribution; 73.3% unit-value contribution	Accounting decomposition; not causal.
BACI food/agriculture trade, 2024	Exports US$8.63 bn; imports US$8.46 bn; balance +US$0.175 bn	Calendar-year BACI aggregate, not PBS fiscal-year balance.
Largest BACI food/agri import partner	Indonesia, ~31.8% of import-direction value	Partner concentration is relevant to supply-chain resilience.

10. Food Technology, Post-Harvest Science, Preservation, Storage and Value Retention

10.1 Why Food Technology and Preservation Belong Inside Food Security

Preservation determines how much of the biological output produced with scarce water and land remains usable. A kilogram of fruit lost after harvest represents not only lost food and revenue but also the water, fertilizer, energy, labor, packaging and transport already invested in it. Preservation is therefore part of production efficiency and water productivity, not merely a logistics issue. Food technology is therefore treated here as the science and engineering that preserve safety, nutritional quality, saleability and value after harvest. The relevant system begins at harvest and extends through handling, cooling, storage, processing, packaging, transport, distribution and final market access.

10.2 Deterioration Mechanisms and Control Variables

The preservation framework covers respiration, transpiration, ethylene action, enzymatic change, oxidation, microbial growth, insects, mould and mycotoxins, moisture migration and mechanical damage. Control variables

include temperature, relative humidity, moisture content, water activity, oxygen/carbon dioxide concentration, ventilation, sanitation, packaging permeability and time. Commodity-specific requirements are essential because conditions suitable for dry grain are not appropriate for fresh mango, raw milk or fish. The expanded framework also records process intensity and technology readiness: microbial-log reduction for validated treatments, shelf-life extension, cold-chain excursion frequency, energy intensity, packaging performance, capex/opex and evidence of pilot versus commercial deployment.

Table 10.1: Preservation and storage methods, applications, advantages and limitations.

Method	Typical products	Advantages	Limitations / risks
Dry storage / warehouses	Grains, pulses, spices	Low capital; flexible	Pests, moisture, mould, quality loss if poorly controlled
Silos / aerated bulk storage	Wheat, maize, grains	Large-scale strategic storage; monitoring and mechanization	Capital cost; management and energy requirements
Hermetic storage	Grains/pulses/oilseeds	Suppresses insects with low chemical use; scalable	Requires sufficiently dry product and intact seals
Pre-cooling + cold storage	Fresh fruits/vegetables, dairy, meat, fish	Slows respiration/microbial growth; extends market window	Energy/capital cost; power reliability; chilling injury for some produce
Controlled atmosphere (CA)	Apples and selected long-storage fruits	Can substantially extend storage life	High capex/skill; commodity/cultivar-specific gas limits
Modified-atmosphere packaging (MAP)	Fresh produce and selected foods	Slows gas exchange/oxidation; retail compatible	Film permeability and temperature must be matched to respiration
Edible coatings / films / waxes	Apples, mangoes, citrus, bananas and other produce	Reduces moisture loss/gas exchange; can carry approved antimicrobials/antioxidants	Poor formulations may impair gas exchange or cause off-flavour/physiological injury
Drying/dehydration	Dates, apricot, mango, raisins, vegetables, fish, spices	Long shelf life; lower weight; value addition	Quality/nutrient/color changes; hygiene and energy issues
Freezing / IQF	Vegetables, fruit pieces, meat, fish	Long storage; export/value-add opportunity	High energy need; texture/drip/freezer-burn risks
Canning / retort	Fruits, vegetables, prepared foods	Long ambient shelf life; reserve potential	Heat effects; packaging/process-control cost
Pasteurization / UHT / drying	Milk, juices, liquid foods	Safety and major shelf-life extension	Equipment, packaging and process-control requirements
Fermentation / pickling	Dairy, vegetables, specialty foods	Relatively low-cost preservation and diversification	Requires controlled hygiene, pH/salt and consistent processing
Irradiation where approved	Spices/selected produce	Pathogen/insect reduction; quarantine applications	Regulation, infrastructure, dose control, acceptance
Edible coatings / films	Mango, citrus, tomato and other fresh produce	Low-material barrier to moisture/gas exchange; may carry active compounds	Formulation/cultivar specific; sensory, regulatory and scale-up constraints
Active / intelligent packaging	Fresh produce, meat, dairy and packaged foods	Can control oxygen/ethylene/moisture and provide freshness/time-temperature information	Material cost, validation, migration/recycling and data-system requirements
High-pressure processing (HPP)	Juices and selected high-value foods	Microbial control with limited thermal damage; fresh-like quality	High capital cost; product/spore limitations; specialist operation
Pulsed electric fields (PEF)	Pumpable foods / juices	Non-thermal electroporation; potential quality and energy advantages	Product suitability, equipment cost and validation requirements
Cold plasma / UV-C / ozone	Fresh produce surfaces and packaging	Low-temperature surface decontamination options	Dose uniformity, quality injury, worker safety and regulatory pathway
IoT / digital cold chain	Fresh produce, dairy, meat, fish, export logistics	Continuous time-temperature monitoring, traceability and predictive shelf-life potential	Connectivity, sensor calibration, data governance and adoption cost

10.3 Edible Coatings and Films as a Specific Horticultural Module

Edible coatings and surface films merit explicit treatment because they can be important for high-value fresh fruit. Reviews indexed by FAO AGRIS describe coatings based on proteins, polysaccharides and lipids that form a barrier to moisture and gas exchange and may reduce microbial growth or delay senescence. Application may be by dipping, spraying or brushing, and performance depends on the fruit, cultivar, coating formulation, temperature and storage environment. The synthesis evaluates coatings through measured outcomes-weight loss, firmness, color, decay rate, soluble solids/acidity, shelf-life extension and cost-rather than treating any coating as universally beneficial (Meghachitra et al., 2025; Pham et al., 2023). Recent research also combines coatings with biocontrol agents, natural antimicrobials and bio-based films. These are treated as intervention-specific evidence: performance must be tied to commodity, cultivar, formulation, temperature, atmosphere and trial design, and research evidence must not be presented as national commercial adoption without independent deployment data.

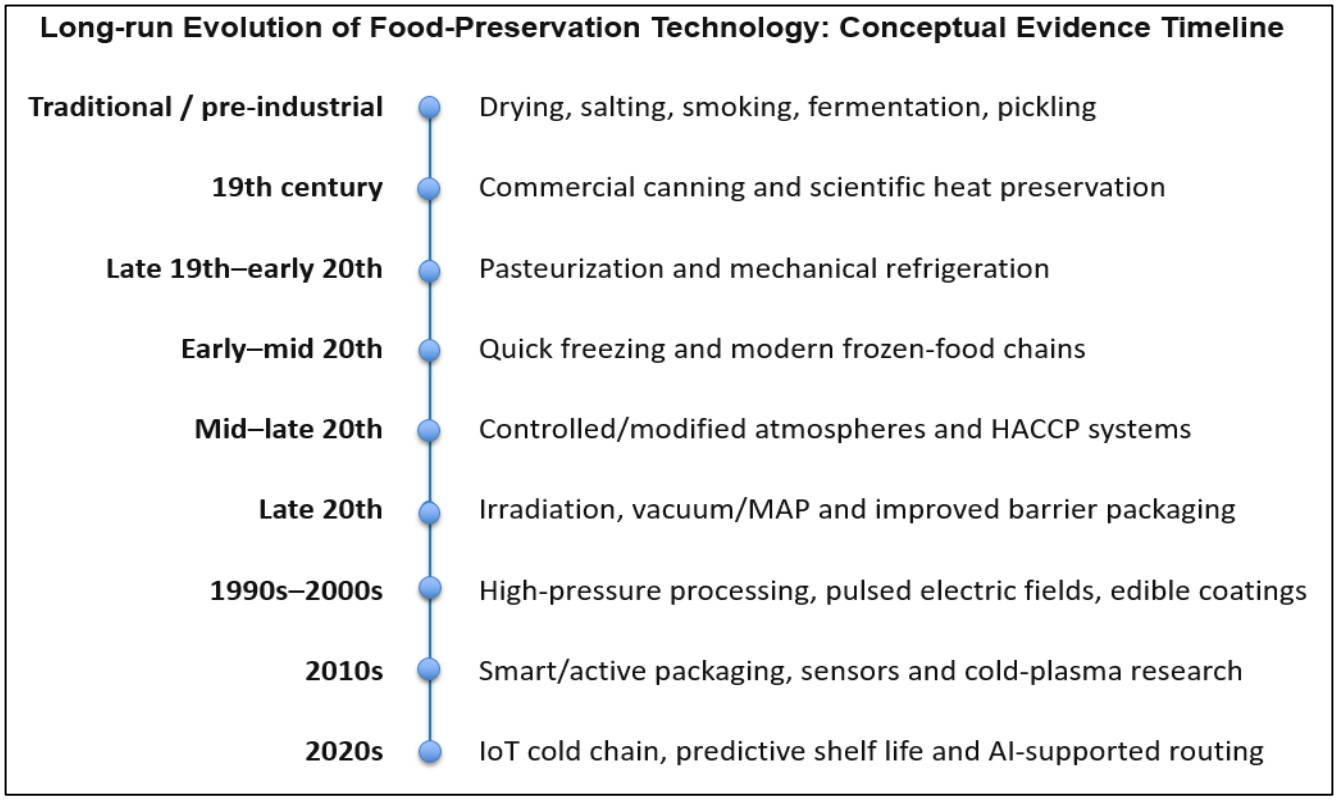


Figure 10.1: Long-run evolution of food-preservation technology: conceptual evidence timeline.

Source / preparation note: Author synthesis from FAO/Codex food-processing and storage guidance, FDA alternative-processing references and recent FAO AGRIS preservation reviews. Periods are broad evidence eras, not precise invention dates; the figure is historical context rather than a 2000-2025 statistical series.

Interpretation: *Preservation science has developed from low-energy traditional methods into integrated systems that combine temperature, atmosphere, process control, packaging, sensing and digital decision support. The analytical question for Pakistan is therefore not whether an advanced technology exists globally, but whether a technology is technically suitable, economically defensible, regulated, available at commercial scale and supported by local cold-chain and quality-control capacity.*

10.4 Cold Chain, Packaging and Emerging Food Technologies

The expanded module covers pre-cooling, cold rooms, refrigerated transport, controlled and modified atmospheres, vacuum/MAP, active and intelligent packaging, irradiation, HPP, PEF, cold plasma, UV-C/pulsed light/ozone, IoT

temperature logging and predictive shelf-life/routing. Mature technologies such as refrigeration, freezing and atmosphere control are distinguished from advanced or research-stage systems. For Pakistan, adoption status is verified independently of international technical feasibility.

10.5 Shelf Life, Expiry and Safety

Shelf life is not represented by one generic expiry table. It is conditional on product form, processing, packaging, storage temperature, humidity and microbial/chemical stability. The database distinguishes quality dating from safety limits and preserves the wording used by the relevant standard or source. Food-safety analysis follows preventive hazard-control principles such as Codex General Principles of Food Hygiene and HACCP, supplemented by product-specific standards. A starter evidence table has now been added for selected Pakistan-relevant commodities using FAO condition-specific storage guidance; these values are benchmarks for defined temperature/RH/product states, not universal expiry claims.

Table 10.2: Condition-specific storage-life benchmarks for selected Pakistan-relevant horticultural products.

Commodity	Product/form	Storage condition	Approx. life	Interpretive note
Apple	Fresh whole fruit	-1 to 4°C; 90-95% RH	~1-12 months	Wide cultivar/system range; CA can extend selected cultivars
Mango	Fresh whole fruit	13°C; 85-90% RH	~2-3 weeks	Chilling injury below suitable commodity temperature
Tomato	Mature-green	18-22°C; 90-95% RH	~1-3 weeks	Ripening stage strongly changes optimum conditions
Tomato	Firm-ripe	13-15°C; 90-95% RH	~4-7 days	Short market window; decay/chilling control critical
Onion	Dry bulb	0-5°C; 65-70% RH	~6-8 months	Curing, ventilation, moisture and sprouting control required
Potato	Fresh-market tuber	4-7°C; 95-98% RH	up to ~10 months	Processing potatoes require different temperature management
Banana	Green, CA example	~2% O2 / 5% CO2; ethylene scrubbed	~4-6 weeks	Technology-specific CA example; local cultivar validation required

Note. Starter benchmarks derived from FAO horticultural storage guidance. Values are deliberately condition-specific and cannot be interpreted as generic expiry dates. Local cultivar, maturity, packaging and handling conditions must be retained in the final evidence table.

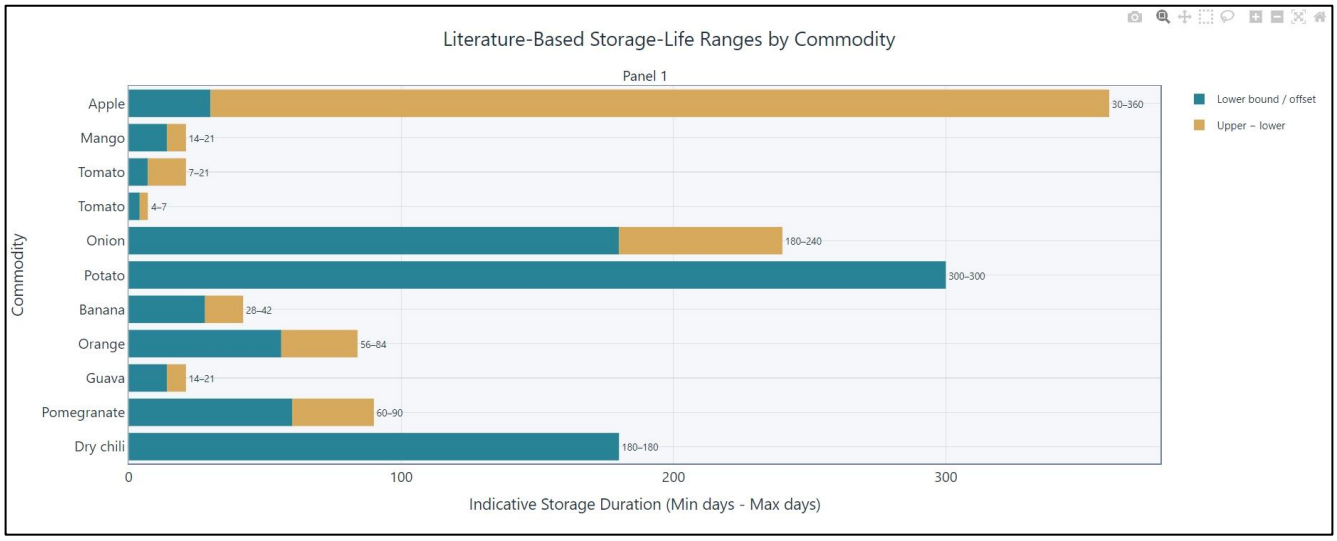


Figure 10.2: Condition-specific storage-life benchmarks for selected Pakistan-relevant produce.

Source / preparation note: FAO storage-of-horticultural-crops guidance summarized in Table 10.2. Storage-life ranges were converted to approximate days only for visual comparability; the x-axis is logarithmic because apple/onion/potato storage periods are much longer than fresh tomato/mango ranges.

Interpretation: *The comparison illustrates why preservation analysis cannot rely on a single concept of 'shelf life'. Appropriate technology differs sharply by commodity and maturity stage: a few days matter for ripe tomato, while properly managed onion, potato and some apple systems can support months of storage. This has direct consequences for infrastructure design, electricity demand, inventory turnover and seasonal price smoothing.*

10.6 Pakistan Alignment with International Post-Harvest Practice

Pakistan is compared domain-by-domain rather than assigned one food-technology score. The comparator framework observes cold-chain infrastructure, grain storage, fresh-fruit technology, vegetable preservation, dairy chilling/processing, meat and seafood cold chains, coatings/packaging, advanced non-thermal processing and digital monitoring. Comparator countries vary by commodity and technology: India, China, Türkiye, Egypt and Morocco provide regional or climatic context; Spain and the Netherlands provide high-value horticulture/logistics benchmarks; Australia provides cold-chain and advanced regulatory/technology examples. Quantitative comparison contains matched definitions and actual source years.

Table 10.3: Food-technology comparator framework for Pakistan.

Domain	Definition / calculation basis	Core metrics	Comparator strategy
Cold-chain infrastructure	Pre-cooling, cold rooms, reefer transport, monitoring	Capacity, utilization, chain continuity, energy/loss reduction	India, China, Türkiye, Egypt, Morocco, Spain, Netherlands, Australia
Fresh-fruit technology	CA/MA, grading, waxing/coatings, export treatment	Shelf-life extension, rejection, quality grade, loss	India, China, Türkiye, Spain, Australia
Vegetable preservation	Curing, ventilated/cold storage, drying, canning/freezing	Loss, seasonal price spread, processing yield	India, China, Egypt, Türkiye
Dairy cold chain	Milk chilling, pasteurization, UHT, powder	Chilling/processing coverage, spoilage, energy	India, Türkiye, Netherlands, Australia
Advanced processing	HPP, PEF, cold plasma, smart/active packaging	Process validation, microbial effect, cost/energy, maturity	Technology-specific international benchmarks
Digital preservation	IoT logging, smart packaging, predictive shelf life	Excursions, traceability, forecast error, waste avoided	Digitally mature supply chains; Pakistan readiness assessed separately

Source / preparation note: comparator architecture. Country selection is functional and technology-specific; it is not a ranking and is populated only where comparable numeric definitions are documented.

10.7 Preservation Economics and Embedded-Resource Value

10.7.1 Incremental preservation appraisal and uncertainty

For commodity c, Qc denotes eligible throughput, L0,c baseline post-harvest loss fraction, L1,c loss fraction after intervention, and Pc the relevant unit value. The gross recoverable value is Qc × (L0,c − L1,c) × Pc. Incremental net annual benefit subtracts extra storage, cooling, packaging, maintenance, distribution and financing-related operating costs, and adds only separately evidenced quality premiums or avoided handling costs. Investment appraisal discounts annual incremental cash flows and deducts initial investment to obtain net present value (NPV); equivalent annual value and payback are supplementary rather than substitute measures. Embedded water and energy are reported separately to avoid double-counting economic benefits. The companion workbook provides an explicit scenario-input register; unverified numerical assumptions remain blank.

Sensitivity analysis varies baseline and post-intervention losses, eligible throughput, price, operating cost, capital cost and discount rate. When assumptions come from different commodities or countries, the results are illustrative scenarios and must be identified as such; they are not realized savings for Pakistan.

The existing preservation-economics framework remains central. Avoided loss is translated into retained tonnes, retained market value and-where crop-water productivity is defensible-embedded water preserved. Technology comparisons pair these benefits with capex, opex, energy intensity, utilization, maintenance and financing assumptions so that technically effective but uneconomic options are not presented as preferred investments.

The macro-financial layer adds an explicit energy-price and foreign-exchange sensitivity to preservation economics. Cold rooms, refrigerated transport, controlled atmospheres, milk chilling and processing can reduce losses while

increasing electricity or fuel exposure. Benefit-cost and NPV models therefore needs to test both avoided-loss value and plausible energy/exchange-rate shocks rather than treating operating cost as fixed.

Table 10.4: Preservation-economics metrics and calculation definitions.

Preservation metric	Planned definition
Post-harvest loss rate	Lost quantity / quantity entering a supply-chain stage
Quality downgrade rate	Quantity downgraded / quantity entering stage
Shelf-life extension	Storage life with intervention minus baseline life
Storage cost intensity	Annualized storage cost / tonnes stored / storage time
Energy intensity	kWh per tonne-day or per kg processed
Loss value avoided	Baseline loss value minus post-intervention loss value
Embedded water preserved	Avoided food loss / crop water productivity
Benefit-cost ratio	Discounted avoided losses + added value / discounted costs
NPV / payback	Long-run and simple investment appraisal
Seasonal price smoothing	Change in peak/off-season price spread associated with effective storage

Calculation framework used for the screening economics: *For preservation/storage cases: Recovered quantity = annual throughput x (baseline loss - post-intervention loss); gross annual benefit = recovered quantity x unit value + separately evidenced other benefits; net annual benefit = gross annual benefit - incremental OPEX; NPV = -CAPEX + sum of discounted annual net benefits; and simple payback = CAPEX / annual net benefit where annual benefits are constant and positive. The break-even recovered-unit value is the unit value that sets NPV to zero at the stated discount rate and project life.*

For irrigation/water screening: water saved = annual water delivered x (baseline loss - after-intervention loss); physically recoverable water = water saved x recoverable share; gross economic benefit = recoverable water x marginal economic value per m3; net annual benefit = gross benefit - incremental OPEX; and NPV discounts those benefits against initial CAPEX. Economic water value is not automatically cash revenue, and water saved is counted only to the extent that it is physically recoverable and can be productively reused.

10.7.2 Preservation and irrigation investment screening results

Three multi-year cases were evaluated using discounted cash flow, payback, break-even and sensitivity analysis. Their purpose is methodological and comparative. AG01 and AG02 are preservation/loss-reduction cases; AG03 is an irrigation/water-recovery case. None is a verified realized investment, and their NPVs must not be added together because they have separate physical and financial scopes.

Table 10.5: Illustrative preservation and irrigation investment screening.

Case	Screening application	NPV	IRR	Simple / discounted payback	Break-even value	Interpretation
AG01	Wheat storage / loss reduction	+$221.5k	24.40%	3.64 y / 5.06 y	$221.59 per recovered unit	Positive under base assumptions; throughput and unit value are major sensitivities.
AG02	Rice drying / improved handling	-$103.6k	7.19%	6.96 y / not reached	$450.95 per recovered unit	Below the 12% hurdle in the base case; requires higher unit value/throughput or lower CAPEX/OPEX to become attractive.
AG03	Canal / irrigation water recovery	-$74.3k	9.13%	8.00 y / not reached	$0.394 per recoverable m3	Below the 12% hurdle; highly sensitive to physical recoverability and marginal economic water value.

Source / preparation note: agricultural and food economics assessment. AG01 assumptions include 10,000 units/year throughput, loss reduction from 10% to 5%, US$300/unit value, US$400,000 CAPEX, US$40,000/year OPEX, 12% discount rate and 10-year life. AG02 uses 8,000 units/year, 8% to 3.5% loss, US$400/unit, US$550,000 CAPEX, US$65,000/year OPEX, 12% and 10 years. AG03 uses 2.5 million m3/year delivered water, 28% to 18% loss, 100% recoverable share, US$0.35/m3 marginal value, US$500,000 CAPEX, US$25,000/year OPEX, 12% and 15 years. All are illustrative screening assumptions until replaced with verified project evidence.

The contrast across the three cases is analytically useful. AG01 clears the assumed hurdle and retains a positive NPV even under many one-way sensitivity combinations, whereas AG02 and AG03 fail the 12% base hurdle despite positive undiscounted annual operating benefits. This demonstrates why avoided loss or recovered water does not constitute an economic gain without including investment cost, operating cost, timing and the opportunity cost of capital.

10.8 Analytical Programme and Evidence Readiness

The food-technology architecture defines 28 potential outputs, and the evidence base is now sufficiently populated to support a first quantitative results set. the current analysis contains 32 stage-level Pakistan post-harvest loss records from ADB value-chain evidence, broader Pakistan historical/current loss observations, date-specific cold-storage capacity records, selected Pakistan-India comparator studies and technology-advancement evidence. The new figures below therefore move Chapter 10 beyond planning: they summarize observed stage loss patterns, cross-study loss ranges, economic value at risk and documented storage capacity. Additional outputs are added as FAO FLW bulk records, full 2025 primary tables, intervention-effect sizes, energy/cost data and national cold-chain inventories are ingested.

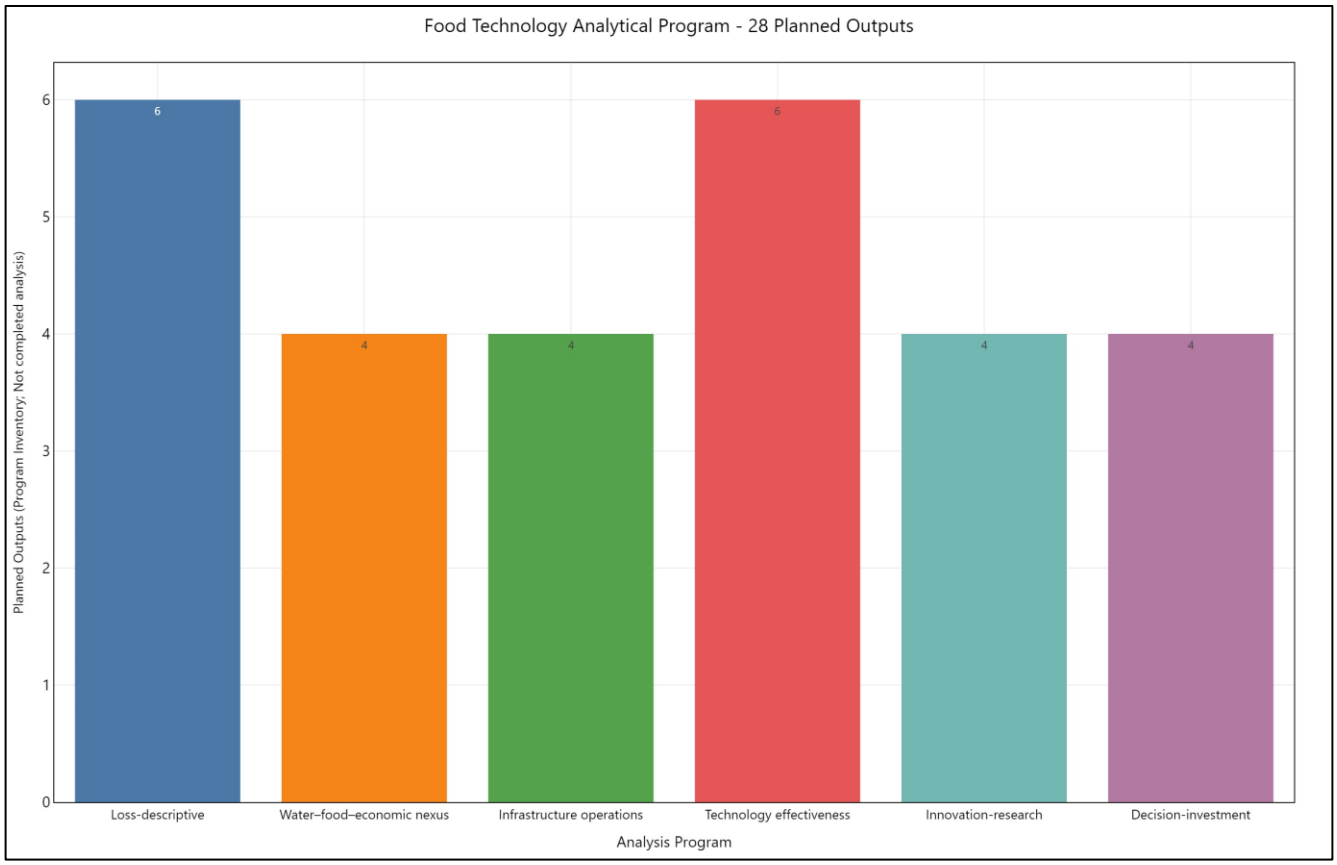


Figure 10.3: Food-technology and post-harvest analytical programme by analysis family.

Source / preparation note: Author-developed catalogue of proposed food-technology analyses. Counts represent planned analytical outputs, not observed outcomes. The final number of figures and tests depends on the completeness and comparability of the underlying evidence.

Evidence boundary: *This is an author-designed programme inventory of planned analyses; the counts are not empirical measurements or completed research outcomes.*

Interpretation: *The major methodological gain from this update is that preservation is no longer represented only by narrative technology descriptions. It now has a reproducible evidence architecture linking source-level loss estimates, intervention effects, shelf life, energy/cost, technology maturity, comparator context, water embodied in lost food and economic value retention.*

10.9 Quantitative Post-Harvest Results Now Available

The completed Stage-1/Stage-2 food-technology datasets now support direct quantitative interpretation. ADB 2022 stage-level evidence shows that losses occur at multiple points in the chain rather than at one single stage. Across the loaded apple varieties, reported overall losses are about 25-26%; the two potato varieties are about 19.2-20.2%. Broader evidence includes a 2019 Pakistan horticulture system estimate of 30-40%, a 2025 onion evidence band of 20-30% depending on current versus improved practices, and study-level Indian comparator estimates for tomato, onion and potato. These figures remain study-specific and cannot be interpreted as a harmonized national ranking.

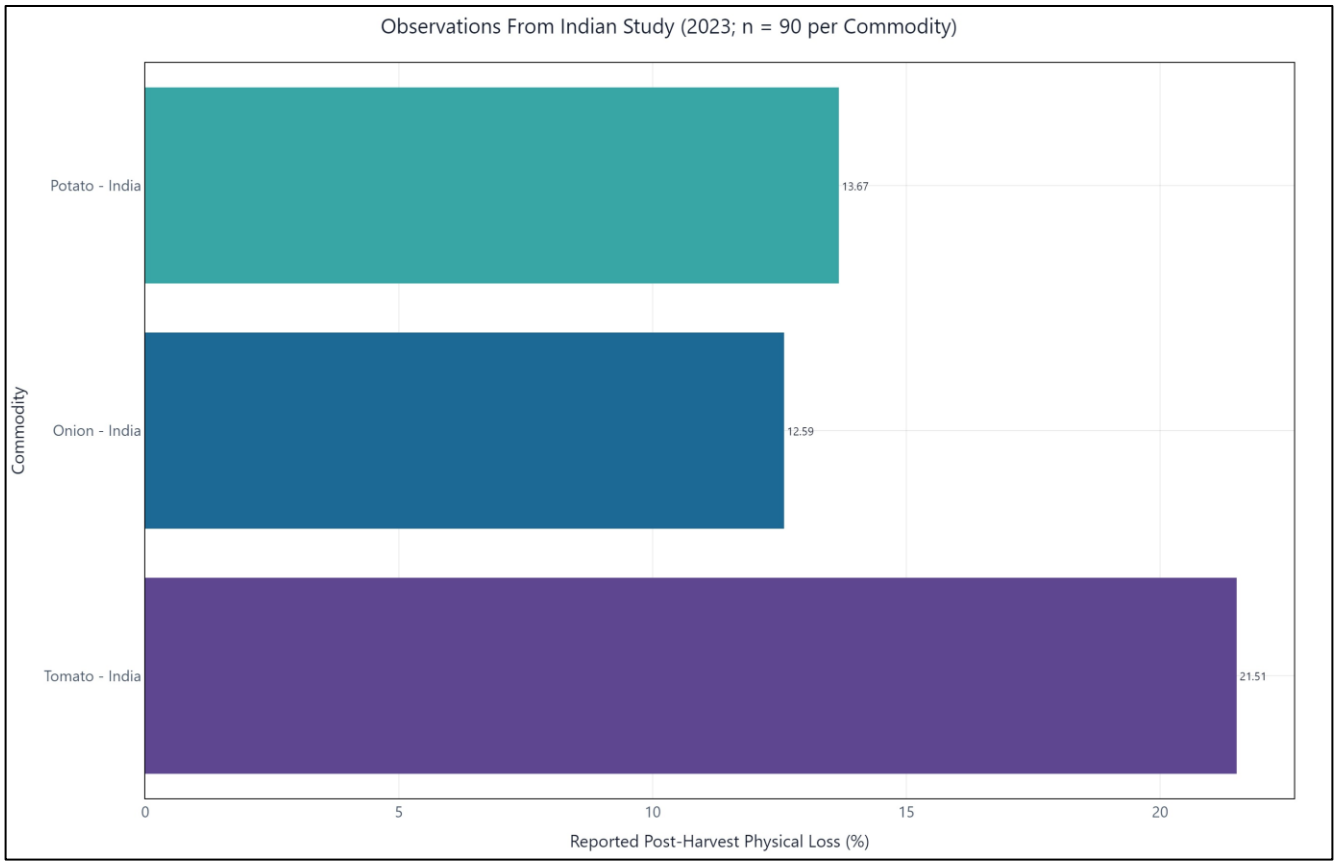


Figure 10.4: Reported post-harvest losses in three India commodity-study observations (2023).

Evidence boundary: *The three observations describe commodity- and location-specific Indian studies; they cannot be extrapolated to Pakistan or national average food loss.*

Interpretation: *The available 2023 India study observations report different physical-loss percentages for tomato, onion and potato. These are study-specific evidence points and should not be interpreted as a comparison of national Pakistan and India loss rates. The accompanying narrative on Pakistan is derived from separate literature and is not measured in this replacement graphic.*

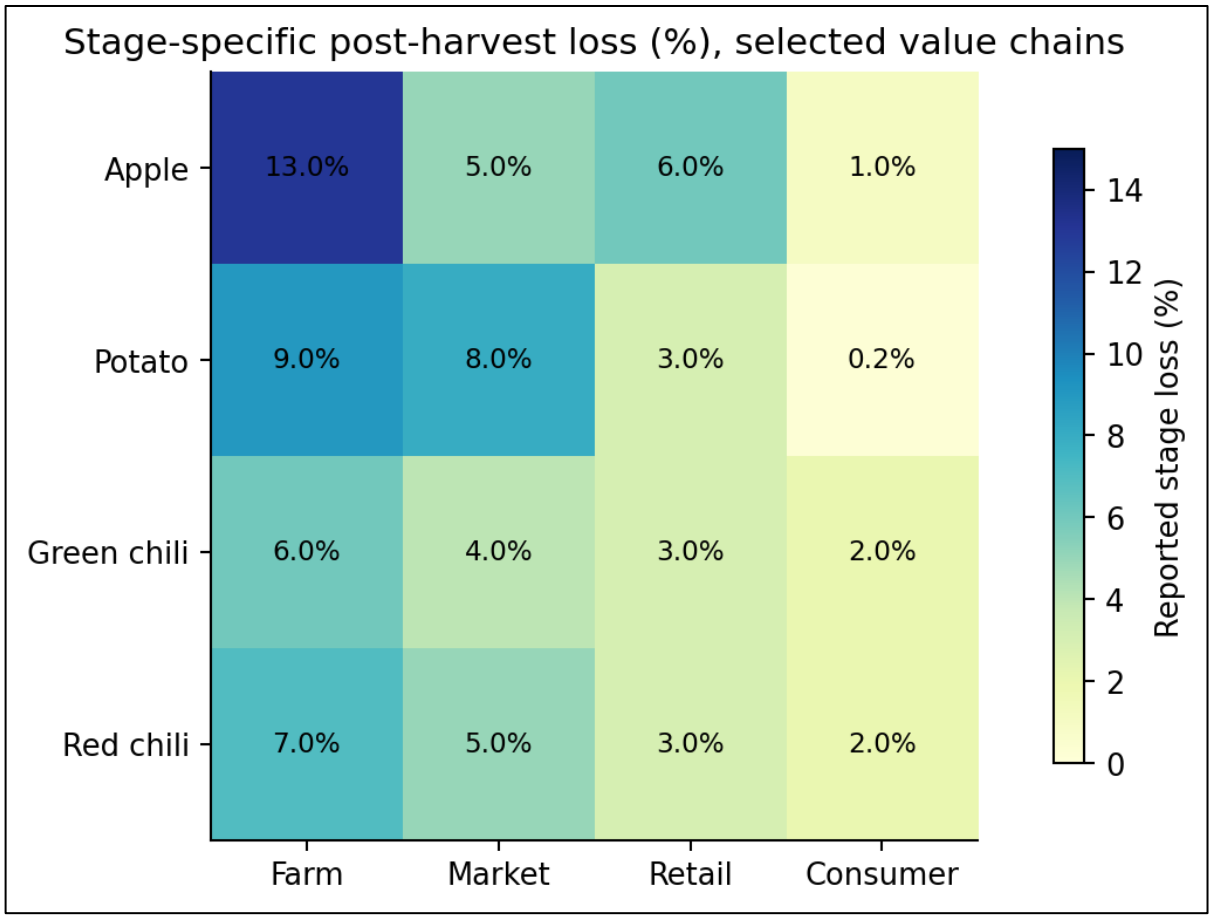


Figure 10.5: Stage-specific post-harvest losses in selected Pakistan value chains, ADB 2022.

Source / preparation note: Asian Development Bank (2022), Pakistan horticultural value-chain assessment; stage-specific post-harvest loss estimates for apple, potato, green chili and red chili. Farm, market, retail and consumer stages are distinguished. Interpretation is conditional on the original study designs and locations.

Interpretation: *Farm-stage losses dominate the loaded apple evidence, whereas potato losses are concentrated at farm and wholesale-market stages. Chili chains show smaller but persistent losses across multiple stages. The practical implication is that cold storage alone cannot address the complete problem: harvest handling, grading, transport, wholesale practice, retail management and consumer handling can each contribute to retention.*

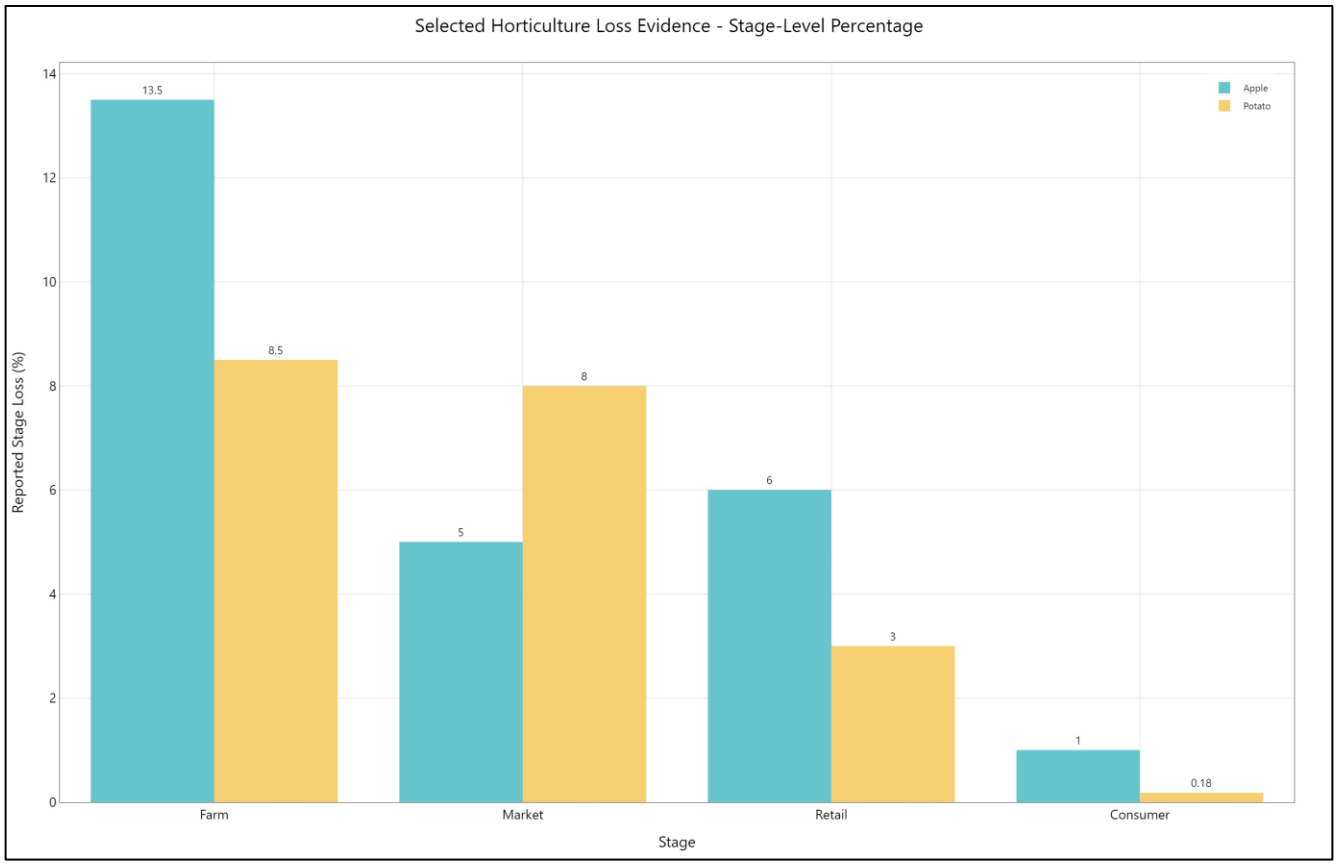


Figure 10.6: Stage-specific post-harvest losses for selected apple and potato study records (descriptive; not national annual economic loss).

Evidence boundary: *Displayed stage values are descriptive averages of small numbers of study records. Stage percentages must not be summed as an economy-wide loss rate.*

Interpretation: *The displayed stage-specific loss proportions identify different points of vulnerability within the sampled apple and potato value chains. The figures are not national annual totals, do not measure USD-denominated aggregate loss, and do not demonstrate the economic return to storage investments. The previously quoted sector-level loss and savings values require separate source verification.*

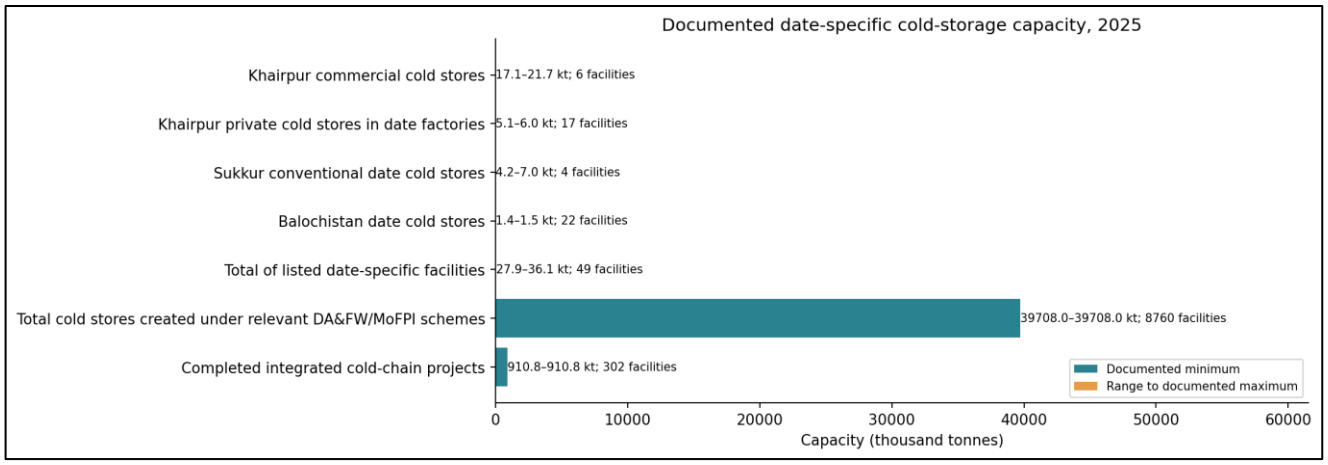


Figure 10.7: Documented Pakistan date-specific cold-storage capacity, 2025.

Source / preparation note: Trade Development Authority of Pakistan, Dates: Production, Consumption, Exports & Potential; author aggregation. The evidence identifies 49 date-related facilities across Khairpur, Sukkur and Balochistan, with an estimated combined capacity of 27.9-36.1 thousand tonnes. This commodity-specific estimate is not Pakistan's total cold-storage capacity.

Interpretation: *The date example demonstrates why infrastructure evidence must retain commodity and geographic scope. A national cold-chain assessment requires a wider inventory, but the documented date facilities already allow the synthesis to connect storage capacity with a specific high-value horticultural chain and to identify where later utilization, energy-cost and export-quality analysis can be anchored.*

Figure 8.7 is a conceptual food-loss and embedded-water hotspot illustration. Its shading must not be interpreted as a measured composite or quantitative economic result.

10.10 Full-Life and Point-Forward Investment Evidence and Sensitivities

The investment cases distinguish full-life appraisal from point-forward screening. Full-life valuation requires dated historical capital commitments and cash flows; point-forward valuation considers future incremental investment and benefits as of a defined decision date. Where the two reports employ the same starting investment and projected cash-flow schedule, identical NPV and IRR results are expected and do not constitute independent project validation. AG01-AG03 are illustrative investment screens, not measurements of realized Pakistan project returns.

Valuation and validation boundary. The reported discount rate, recovered commodity or water volume, attributable benefit, utilization and unit value are scenario assumptions unless corroborated with local primary evidence. A positive base-case NPV is conditional on those assumptions; a negative base-case NPV does not demonstrate that the technology or intervention is intrinsically unviable. Field-level CAPEX, OPEX, throughput, actual reduction in losses, usable water recovery, taxes, financing, maintenance, replacement expenditure and residual/closure costs are necessary to support a project decision.

Table 10.6. Project appraisal decision thresholds and material drivers.

Case	Base NPV (US$)	IRR	Hurdle	Primary leverage / caution
AG01 wheat storage	+221.5k	24.40%	12%	Recovered quantity and unit value; positive indicative screen.
AG02 rice drying	−103.6k	7.19%	12%	CAPEX, throughput, energy/OPEX and recovered value; below hurdle.
AG03 irrigation	−74.3k	9.13%	12%	Recoverable m^3 and marginal value of water; below hurdle.

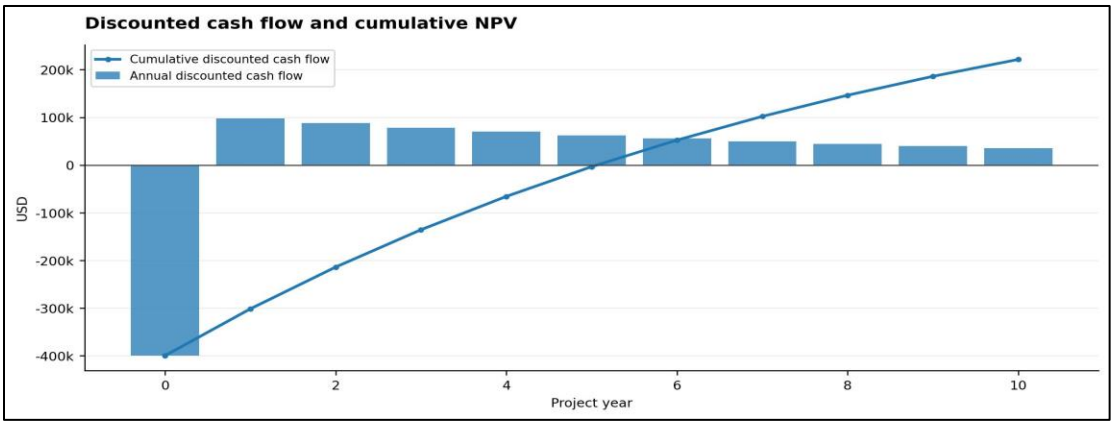


Figure 10.8: AG01 annual discounted cash flow and cumulative NPV under illustrative base-case assumptions.

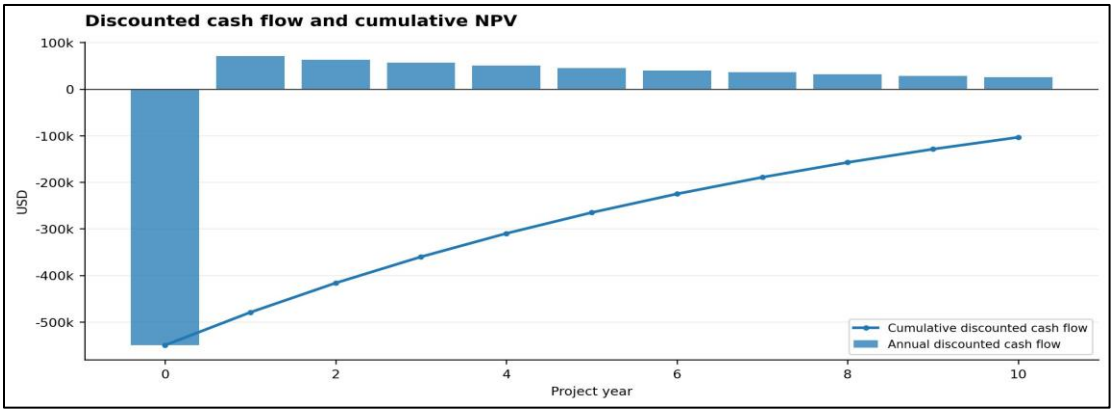


Figure 10.9. AG02 annual discounted cash flow and cumulative NPV under illustrative base-case assumptions.

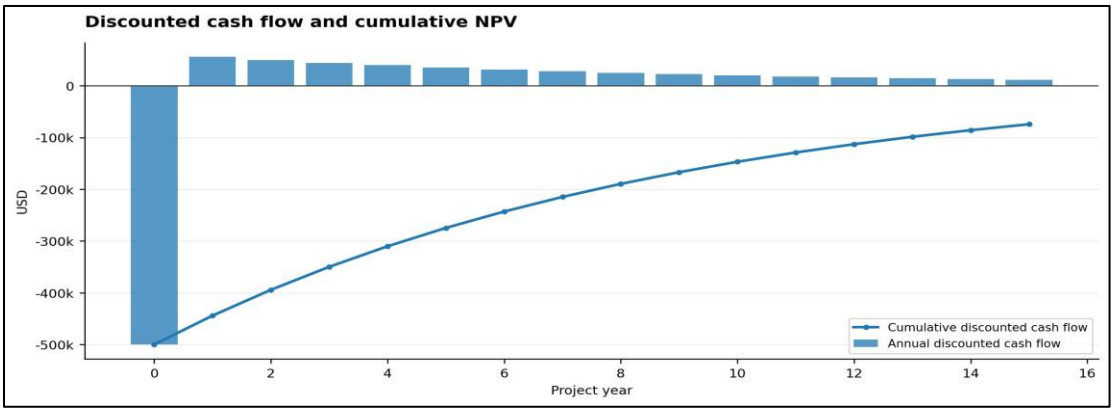


Figure 10.10. AG03 annual discounted cash flow and cumulative NPV under illustrative base-case assumptions.

Interpretation: *NPV and IRR screen investment under specified assumptions, not actual asset value. Reproducible project appraisal also requires audited location-specific CAPEX, OPEX, utilization, tariffs, taxes, financing, degradation, maintenance and end-of-life liabilities. Negative base-case NPV is not proof that the technology is universally uneconomic.*

11. WASH and Domestic Water-Security Context

Agricultural water security and household drinking-water security are related but cannot be collapsed into a single indicator. The Pakistan Census 2023 provides household-level source classifications that can be mapped at province/district level. Census 'improved drinking water' classifications are kept distinct from the WHO/UNICEF Joint Monitoring Programme concept of 'safely managed drinking water', which includes additional service-quality criteria.

The WASH module assesses spatial access, household burden and possible association with irrigation intensity or groundwater dependence without implying causation from cross-sectional correlations. WASH is included because future water security must account for competition among agriculture, domestic use, ecosystems and industry.

11.1 Current Provincial WASH Evidence

Census 2023 evidence shows a high national share of households using the study's 'improved water' classification (about 91.9%) but substantial provincial inequality. Balochistan has the lowest percentage among the listed provinces/territories at about 71.4%, while Khyber Pakhtunkhwa has the largest absolute number of households without improved water in the current provincial summary (about 1.04 million). Punjab and Islamabad Capital Territory exceed 96% improved access. These figures describe source/access classification, not the more demanding WHO/UNICEF definition of safely managed drinking water.

Table 11.1: Improved and not-improved household water access in Pakistan, Census 2023 summary.

Geography	Improved water (%)	Not improved (%)	Households not improved
Pakistan (national reference)	91.93	8.07	3,091,752
Khyber Pakhtunkhwa	82.23	17.77	1,041,489
Punjab	96.59	3.41	676,837
Sindh	92.92	7.08	697,833
Balochistan	71.45	28.55	661,691
Islamabad Capital Territory	96.62	3.38	13,902

The next figures distinguish the percentage of households using improved sources from the absolute number lacking improved water. Figures 11.1 and 10.3 provide province-level GIS views; Figures 11.2 and 10.4 provide corresponding numerical comparisons. These paired perspectives describe both the relative access deficit and the population affected.

Figure 11.1 maps the percentage of households using improved water sources by province. Figure 11.2 retains the numeric comparison and makes the provincial differences directly readable.

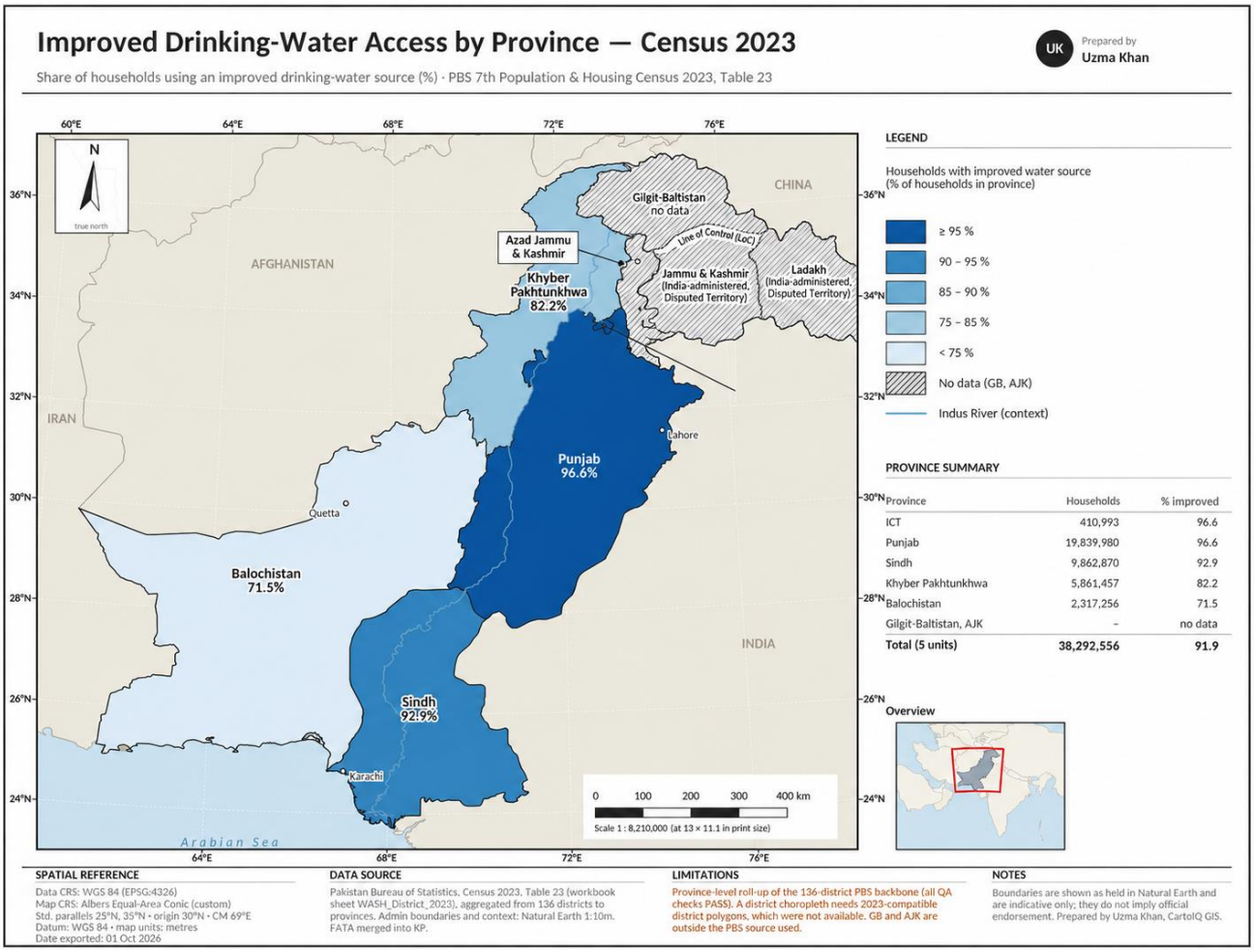


Figure 11.1: Improved drinking-water access by province, Census 2023 (GIS M05).

Improved-water access is high in Punjab, Sindh and ICT in the provincial Census 2023 observations, while Balochistan has a substantially lower share. These differences motivate the subsequent examination of absolute household exposure.

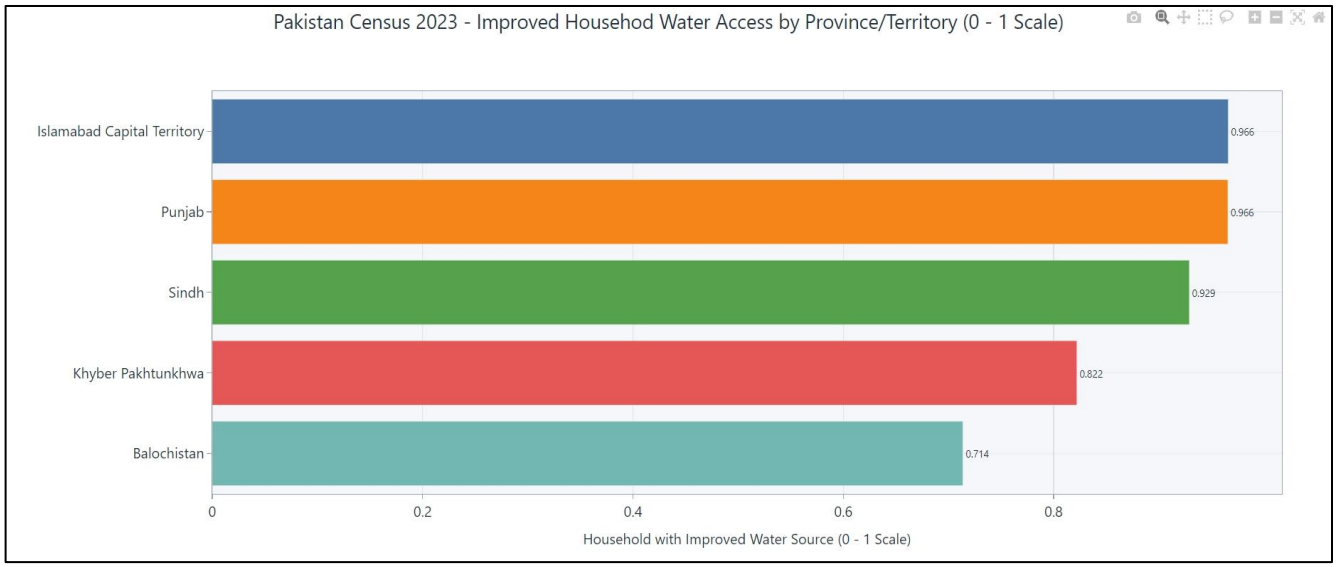


Figure 11.2: Improved-water access percentages across provinces and territories, Census 2023.

The provincial comparison makes relative access differences explicit; it does not by itself indicate how many households lack improved water in each province.

The absolute number of households without improved water is presented geographically in Figure 11.3 and numerically in Figure 11.4. A province may account for a large share of affected households even when its percentage access deficit is below that of another province.

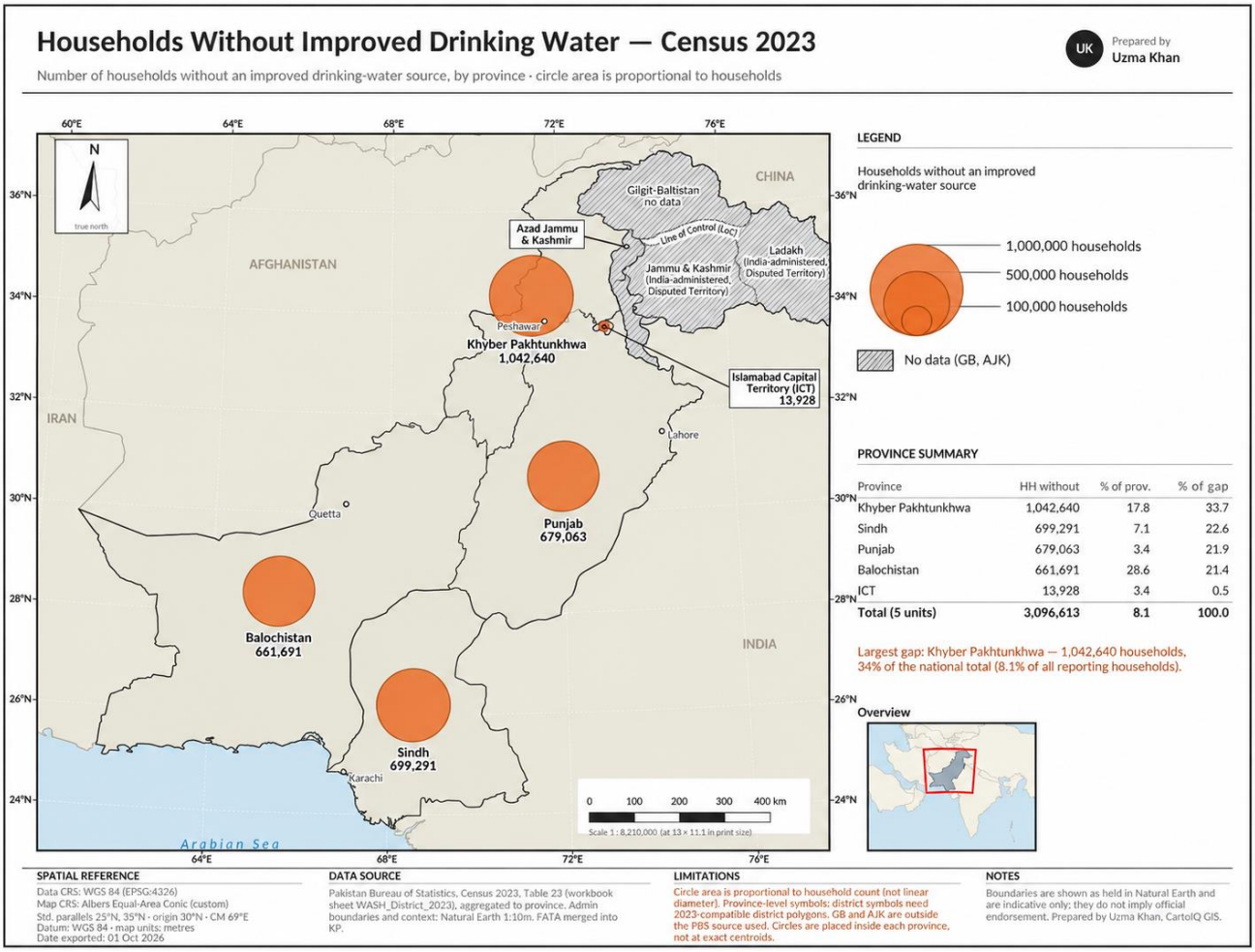


Figure 11.3: Households without improved drinking water by province, Census 2023 (GIS M06).

The provincial Census 2023 totals identify Khyber Pakhtunkhwa as having the largest absolute number of households without improved water, while Balochistan has a more pronounced relative access deficit.

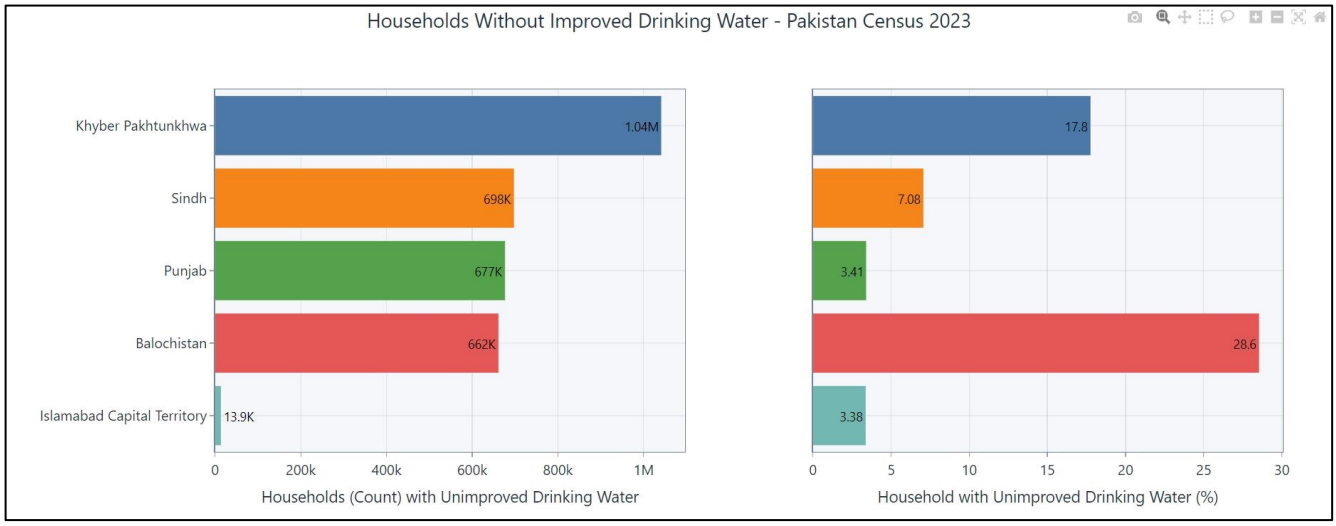


Figure 11.4: Absolute and percentage burden of households without improved water, 2023.

The combination of absolute and proportional burden makes clear why infrastructure planning needs both metrics. Neither measure needs to be substituted for an unobserved district-level distribution.

12. Comparator-Country Rationale

Country selection is purposive rather than a geographically representative sample. The core Pakistan-plus-15 framework assigns countries to regional/agro-climatic peers, irrigation and water-stress analogues, high-value or technology-oriented benchmarks, and extreme-aridity/food-import cases. Supplementary European and biotechnology comparators are introduced for specific questions rather than merged into every calculation. Global population, GDP, financial and trade figures can use the larger source-specific country coverage, but any cross-country analysis must disclose its own included population, vintage, exclusions and missingness. Differences in hydrology, institutional capacity, agricultural structure and reporting methods prevent a simple country-wide best-to-worst interpretation.

No single comparator country is appropriate for every question. The thesis therefore uses functional comparator groups, and countries can enter or leave an analysis depending on data comparability and the research question.

Table 12.1: Functional comparator-country framework used in the synthesis.

Comparator function	Countries	Reason for inclusion
Regional / agro-climatic context	India, China, Bangladesh, Iran, Afghanistan	Regional food systems; monsoon/arid contrasts; shared or similar crop portfolios
Irrigation / water-stress analogues	Egypt, Türkiye, Uzbekistan, Morocco	Irrigated agriculture under water constraints and different institutional/technology settings
Technology / value benchmarks	Spain, Australia, Israel, Netherlands	Water productivity, reuse, basin management, high-value horticulture, protected agriculture and logistics
Special water-security cases	Saudi Arabia, United Arab Emirates	Extreme aridity, food-import strategy, controlled-environment production and desalination context
Supplementary European extension	Italy, France	Mediterranean horticulture, diversified EU agriculture and European breeding/NGT context; used only where relevant
Biotechnology-specific benchmarks	India, China, Australia, USA, Brazil, Argentina, Canada, selected EU systems	Commercial GM adoption, genome editing, regulation, breeding technology and translation from research to farms
Pakistan	Focal country	National, provincial and district analysis plus global comparison

The study does not produce a single 'league table' of countries. Instead it compares specific, documented metrics and identifies context-matched analogues. This avoids treating differences in climate, population, diet, trade structure and resource endowment as if they were directly interchangeable.

Comparator selection is purposive by analytical function rather than a geographic quota. The core quantitative panel remains Pakistan plus 15 countries selected as regional peers, irrigation/water-stress analogues, high-productivity/value benchmarks or extreme water-security cases. Europe is therefore not absent: Spain and the Netherlands are core benchmarks and Türkiye provides a Europe-West Asia bridge. The updated evidence architecture adds Italy and France as supplementary European comparators where Mediterranean horticulture, diversified EU agriculture, breeding systems or the European new-genomic-technique regulatory context are directly relevant. A separate biotechnology benchmark set also uses the United States, Brazil, Argentina, Canada, India, China, Australia and selected European systems. These countries are not automatically inserted into every water regression because technological comparability and hydrological comparability are different concepts.

12.1 Demographic and Rainfall Context for Comparator Interpretation

Comparator interpretation requires demographic and climate context for the full core Pakistan-plus-15 group. In 2025, Pakistan had about 255.2 million people, 36.2% aged 0-14 and 4.4% aged 65+, corresponding to a youth-to-old

ratio of about 8.23. India and China were the most populous comparators, whereas Spain and the Netherlands had much older population structures. The complete 16-country comparison in Table 12.2 spans monsoonal, temperate, arid and hyper-arid contexts. Differences in population structure and rainfall help interpret food demand, labour availability, irrigation constraints and import exposure; they are not measures of agricultural success by themselves.

Table 12.2: Demographic and annual-rainfall context for Pakistan and all 15 core comparator countries, 2025.

Country	Population 2025	0-14 (%)	65+ (%)	Youth / old ratio	Annual rainfall 2025 (mm)
Pakistan	255.2m	36.2	4.4	8.23	372
India	1.464bn	24.2	7.4	3.27	1404
China	1.407bn	15.4	14.9	1.03	833
Bangladesh	175.7m	27.6	6.7	4.12	2081
Iran	92.4m	22.0	8.6	2.56	212
Afghanistan	43.8m	42.6	2.4	17.75	266
Egypt	118.4m	31.6	5.3	5.96	6
Türkiye	85.9m	21.0	10.6	1.98	546
Uzbekistan	37.1m	31.3	6.1	5.13	171
Morocco	38.4m	25.2	8.4	3.00	282
Spain	49.4m	12.6	21.6	0.58	742
Australia	27.6m	17.7	18.1	0.98	455
Israel	10.1m	27.2	12.7	2.14	154
Netherlands	18.1m	14.9	20.9	0.71	709
Saudi Arabia	37.0m	23.6	3.1	7.61	51
United Arab Emirates	11.5m	16.0	1.8	8.89	19

Scope note: *The 16 core countries are shown here; comparable 2025 demographic and annual-rainfall fields are available in the analytical dataset. Supplementary biotechnology, European and trade comparators remain relevant to selected chapters but are not automatically part of this core table. Rainfall figures are country-context indicators, not crop-zone or irrigation-water measurements; sources and vintages must be disclosed when interpreting individual comparisons.*

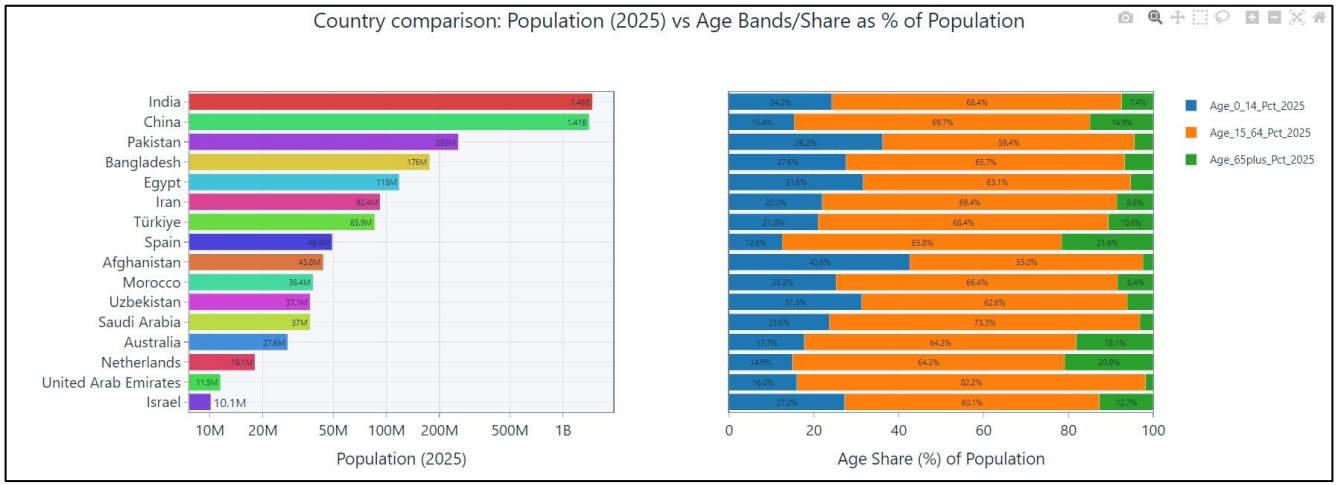


Figure 12.1: Population and age structure of Pakistan and comparator countries, 2025.

Source / preparation note: Integrated international comparator indicators compiled from demographic, precipitation and water/agriculture statistics described in Chapter 4. Values provide contextual cross-country comparisons; they are neither causal estimates nor normalized to equivalent agricultural areas. Figure 12.1 distinguishes total population from age-group proportions.

Interpretation: *Pakistan remains demographically young relative to several benchmark economies, especially China and European comparators. This creates a potentially favorable labor-age trajectory but also implies continued growth in food, water, housing and employment demand.*

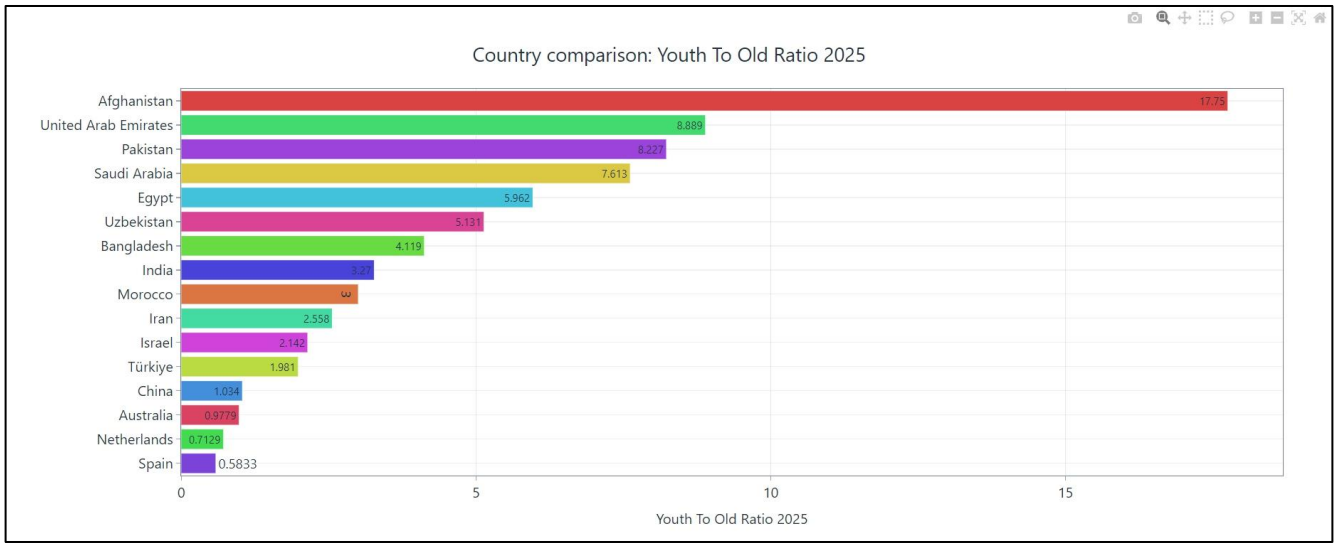


Figure 12.2: Youth-to-old population ratio across comparator countries, 2025.

Source / preparation note: International population and age-structure estimates for 2025, as described in the data-source register. Higher youth-to-older-population ratios indicate a younger age structure, not necessarily a demographic advantage.

Interpretation: *Pakistan has a much higher youth-to-old ratio than aging comparators such as China and several European countries. The indicator is not a welfare ranking; it highlights different future demand, labor-force and dependency structures that matter for food-system planning.*

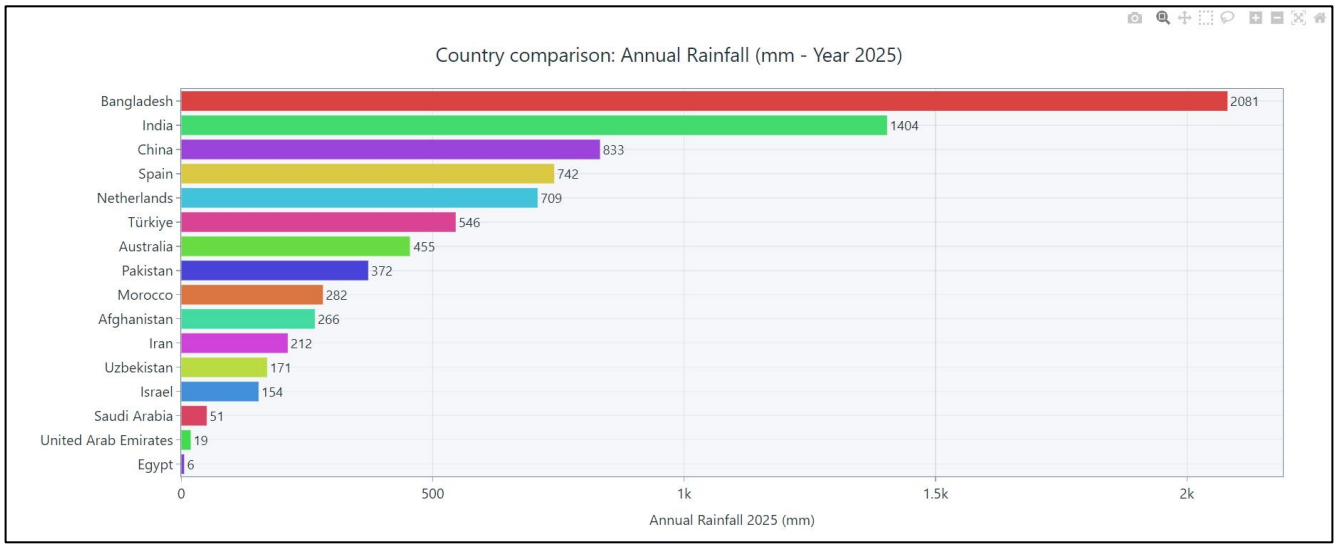
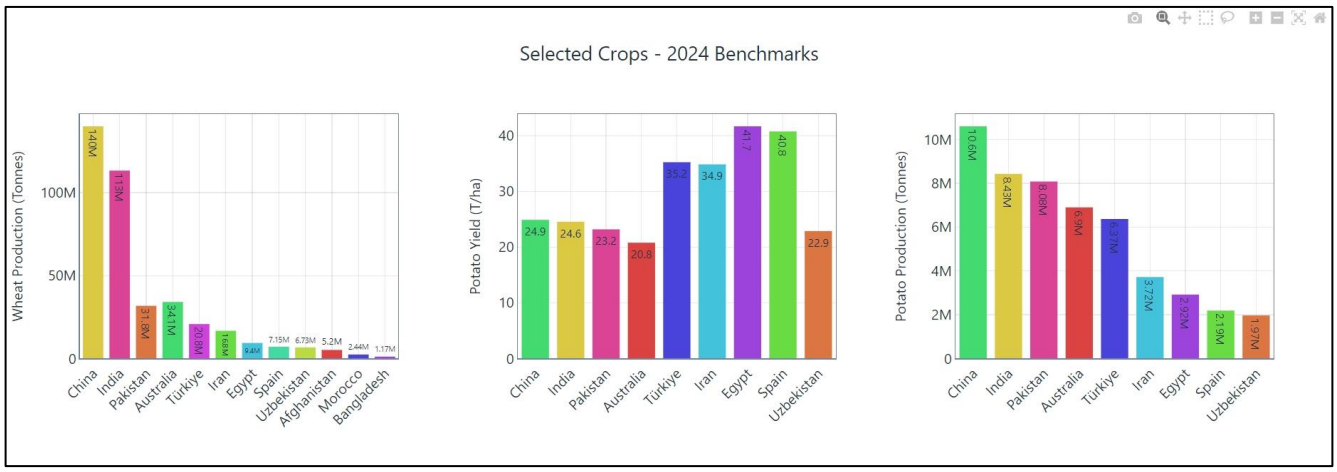


Figure 12.3: Annual precipitation across Pakistan and comparator countries, 2025.

Source / preparation note: International precipitation estimates and CRU climate series. Monthly and seasonal comparisons use consistent climate-series definitions where available; annual comparator values provide broader geographical context and may reflect different periods or methods.

Interpretation: *The comparator set spans extremely different rainfall regimes, from hyper-arid to monsoonal climates. This reinforces the methodological decision to use comparator countries by functional role rather than treating every country as an equally valid climatic analogue for Pakistan.*

Figure 12.4: Selected crop production and yield benchmarks across comparator countries, 2024.



Source / preparation note: International 2024 crop production and yield observations for selected country-commodity combinations. Coverage differs by crop and country; missing observations are not treated as zero. Full cross-country rankings are not justified where comparable coverage is incomplete, and rice definitions require verification before detailed comparisons.

Interpretation: *Crop production volume and crop yield reveal different dimensions of performance. Pakistan is a major wheat producer in the loaded 2024 comparison, while yield benchmarks for selected crops show that smaller producers can outperform larger producers on land productivity; the sparse sheet is used selectively and missing countries remain unfilled.*

12.2 Demographic Transition, Economic Capacity and Food-System Demand

The companion demographic analysis contributes a useful formal insight: the central problem is not simply 'too many' or 'too few' people, but whether population structure is sustainable relative to resources and productive capacity. Pakistan's 2025 population is about 255.2 million, fertility about 3.5 births per woman and youth-to-old ratio about 8.23. This youthful structure implies continued expansion of food, water, education, housing and employment requirements, while older comparator economies face a different constraint set involving workforce replacement, pensions, healthcare and greater automation.

A demographic dividend is therefore conditional rather than automatic. A large future labour force can support growth when education, health, skills, employment and productivity expand with it. Conversely, low fertility and ageing do not remove food-system challenges; they can increase pressure for farm mechanization, labour-saving logistics and specialized diets. For the synthesis, demographic variables are therefore explanatory context for demand and labour supply, not a country score.

Economic capacity modifies the same demand pathway. Total GDP measures economic scale, whereas GDP per capita better reflects average productive/income capacity. As incomes rise, diets commonly diversify, so water-food planning considers not only how many people will eat but also how the composition, storage, processing and cold-chain requirements of the food basket may change.

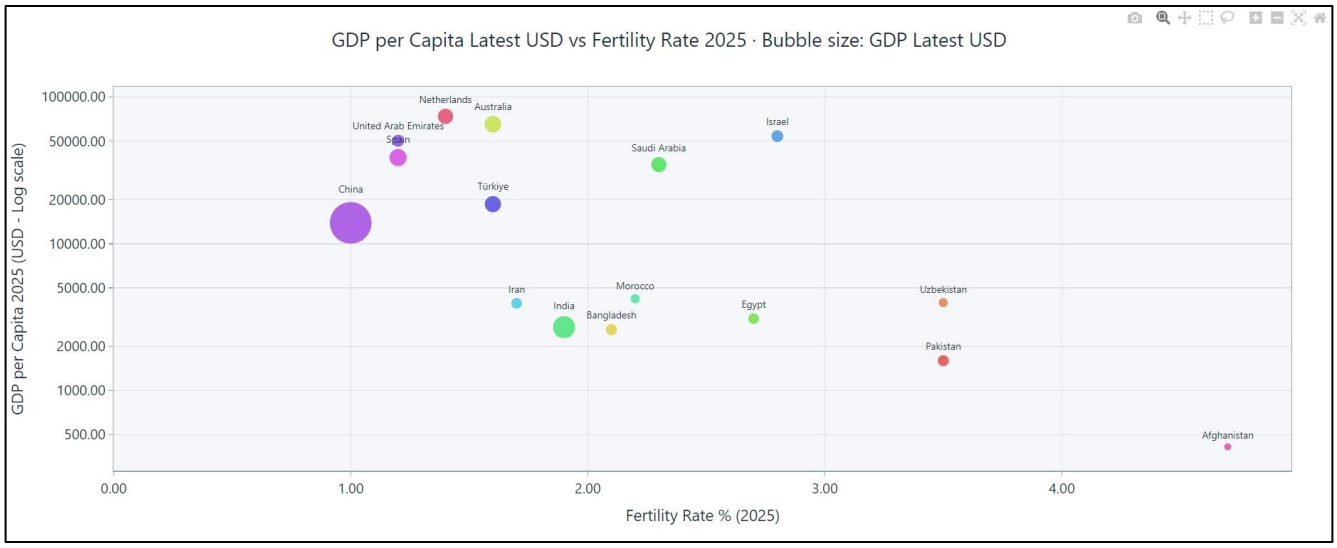


Figure 12.5: Fertility and economic capacity across countries: latest GDP and 2025 demographic context. The chart is contextual, and doesn't imply that fertility causes income

Source / preparation note: International demographic and macroeconomic estimates compiled for the comparison. GDP per capita is estimated from latest available nominal GDP and 2025 population where a directly comparable indicator is unavailable. GDP reference years may differ; this is contextual cross-sectional evidence rather than a harmonized annual panel.

Interpretation: *The global pattern is consistent with very different demographic transition stages, but it cannot be interpreted as evidence that lower fertility mechanically creates prosperity. Pakistan sits in the higher-fertility, lower-income portion of the current cross-section, reinforcing the need to analyze productivity growth, human-capital investment and food-system capacity together with population.*

12.3 Integrated Performance Comparison: Water, Agriculture and Economic Capacity

The demographic and rainfall results in Table 12.2 provide context, but do not establish relative food-system performance. Table 12.3 extends the same 16-country core group to water-stress exposure, economy-wide water productivity, agricultural value added per worker and nominal GDP per capita. These are distinct dimensions, not a composite score: annual water stress captures withdrawal pressure, economy-wide water productivity includes activities outside agriculture, and agricultural value added per worker is influenced by prices, exchange rates, employment definitions and economic structure.

Table 12.3: Selected water-resource, agricultural-productivity and economic-capacity indicators for Pakistan and the 15 core comparator countries (latest available observations).

Country	Water stress (%)	Water productivity (US$/m³)	Ag. value added / worker (US$)	GDP per capita (US$)	Indicator coverage
Pakistan	98.1	2.23	3,186	1,596	Context only
India	65.9	4.62	2,159	2,702	Context only
China	41.6	29.39	8,631	13,862	Context only
Bangladesh	5.7	8.52	1,236	2,597	Context only
Iran	80.4	5.26	12,863	3,924	Context only
Afghanistan	54.8	0.76	1,153	414	Context only
Egypt	112.9	5.86	8,942	3,086	Context only
Türkiye	47.9	18.81	13,845	18,599	Context only
Uzbekistan	123.0	3.35	9,913	3,968	Context only
Morocco	18.8	11.95	3,898	4,218	Context only
Spain	43.3	46.44	45,339	38,627	Context only
Australia	4.2	137.04	126,574	65,130	Context only
Israel	119.6	-	118,493	54,026	Context only
Netherlands	14.9	111.30	89,045	73,684	Context only
Saudi Arabia	974.2	36.75	57,181	34,537	Context only
United Arab Emirates	1,437.3	186.07	37,801	50,274	Context only

Interpretation: *In the 16-country comparator analysis, Pakistan records water stress of 98.1% and economy-wide water productivity of approximately US$2.23/m³, compared with India (65.9%; US$4.62/m³), China (41.6%; US$29.39/m³) and Türkiye (47.9%; US$18.81/m³). Egypt and Uzbekistan have water-stress figures above 100%, while Saudi Arabia and the UAE show much higher ratios; these observations require attention to the indicator denominator and do not mean that more water is physically created or that all withdrawal is unsustainable. Stronger economy-wide water productivity in higher-income countries cannot be attributed solely to irrigation technology because economic composition and valuation differ.*

Agricultural labour productivity also varies across the 16 countries, but the US-dollar value-added measure combines agricultural structure, relative prices, employment and exchange-rate effects. It is therefore best used alongside commodity-specific yield (t/ha), crop-specific evapotranspiration or water use (m³/t or kg/m³), loss rates and unit-cost evidence. The selected international crop observations for 2024 provide selected production and yield observations; its uneven country-crop coverage does not justify a complete 16-country ranking for every commodity.

12.4 Food-Trade Exposure and Interpretation of Transferable Practices

Food-import dependence, import-bill sensitivity and trade concentration must be treated separately from water stress or GDP per capita. The current national synthesis documents Pakistan's edible-oil exposure and identifies the importance of FX pressure, while the wider global trade and energy files supply context. However, fully comparable 2024-2025 food-import dependency ratios for every country and a common food-basket definition are not established in Table 12.3. A cross-country food-trade score is therefore intentionally not calculated. A valid future table would distinguish food import value (US$), food imports as a share of merchandise imports, net food trade, selected HS commodity import-dependency ratios, and observation year/source.

Table 12.4: Comparator functions, evidence strength and implications for Pakistan.

Comparator function	Available comparison	Interpretation / application
Regional peers	India, China, Bangladesh; scale, demography and selected crop outputs	Compare crop yields, economic water productivity and import exposure only for matched definitions and periods.
Shared aridity / irrigation pressures	Iran, Egypt, Türkiye, Uzbekistan, Morocco, Afghanistan	Screen water stress, irrigation dependence and resilience; institutional transferability requires local feasibility tests.
High-value agricultural systems	Spain, Netherlands, Australia, Israel	Benchmark productivity, post-harvest systems and technology; distinguish economy-wide from crop-water indicators.
Extreme aridity / import strategies	Saudi Arabia and UAE	Compare food-import/logistics/storage strategies under pronounced renewable-water constraints, without assuming domestic production models transfer.
Food trade and economic capacity	Pakistan plus comparators where reliable HS/basket data align	No full 16-country import-dependency ranking yet; verify commodity coverage, fiscal/calendar periods and trade denominators.

Source / method: Comparator-country selection follows the functional rationale in Table 12.1. Country-level water, demographic, agricultural-productivity and crop observations are drawn from the international statistical source families documented in Chapter 4. Potential transferability remains a hypothesis requiring crop-, location- and project-specific validation.

Synthesis implication. *Pakistan's strategic priority is not to copy a single best-performing country. The available comparisons motivate a portfolio of tests covering reliable irrigation services, groundwater management, commodity-specific water and labour productivity, loss prevention, cold-chain/storage systems, trade resilience and technology adoption. These benchmarks identify research and investment questions; they do not establish causal impacts or numerical gains. The 2030/2040/2050 pathways in Chapter 15 remain conditional on harmonized evidence, project feasibility and calibrated scenarios.*

12.5 Geographic Visualization of Selected Country Benchmarks

Figures 12.6 and 12.7 retain the seven-country geographic subset originally plotted in this synthesis. The full Pakistan-plus-15 comparator framework is now reported in Tables 12.2 and 12.3, and the maps must not be read as depicting all 16 observations. Grey countries have no reported value on these selected maps; map values are not world totals or regional averages.

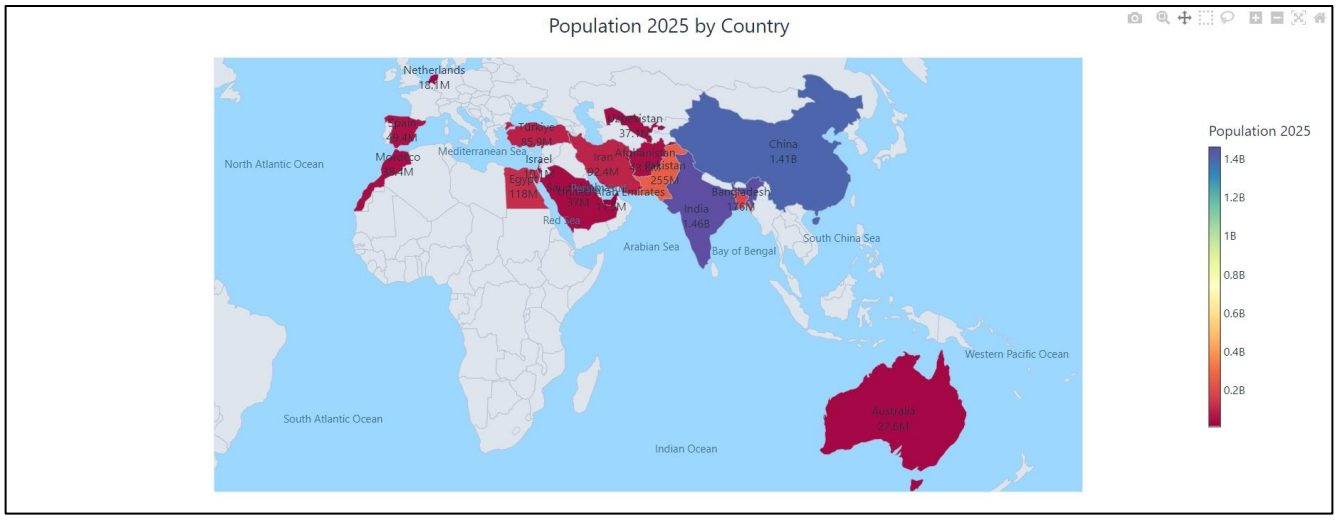


Figure 12.6: Selected-country choropleth: Population aged 0-14 years (%), 2025; seven-country reported data only.

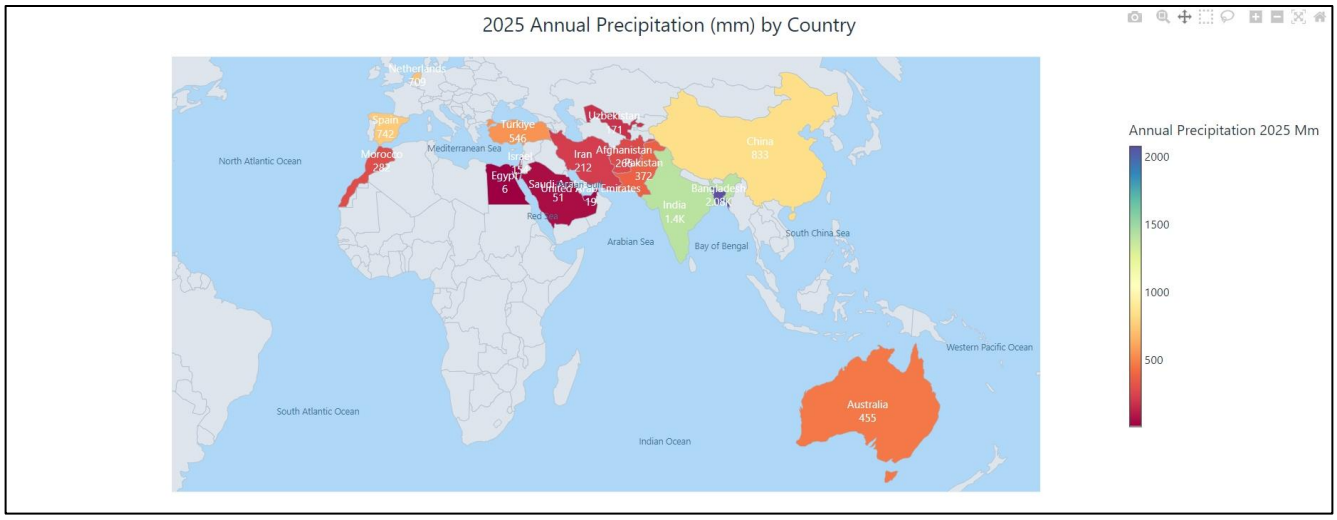


Figure 12.7: Selected-country choropleth: Annual precipitation (mm), 2025; seven-country reported data only.

Source: Selected comparator-country statistical observations described in Tables 12.2 and 12.3; Natural Earth geographic boundaries. The maps show the subset for which values could be mapped consistently. Unmapped countries are not assigned estimated values, and the cartographic display should not be interpreted as an exhaustive country ranking.

13. Statistical and Econometric Analysis Framework

13.1 Analytical Implementation

The statistical framework is designed to match the data-generating structure. The The analytical framework covers food science, time series, spatial analysis, evidence synthesis and economic comparisons. Research V18.0 recognizes the completed merchandise-trade, fuel-exposure, current-account, reserve and exact-HS fields while prioritizing

MMbbl/d for oil and MMscf/d for gas; TWh/year is retained for traceability. The dedicated Economics template continues to provide deeper macroeconomic/time-series/economic diagnostics. These tools are analytical workstations; method selection still follows statistical assumptions rather than software availability.

13.2 Data-Quality and Descriptive Layer

Every analysis begins with data coverage, missingness, units, duplicate keys, outliers, distribution shape and source consistency. Descriptive reporting includes N, mean, standard deviation, median, interquartile range, minimum, maximum, coefficient of variation and data-coverage years as appropriate. Variables with structural missingness are not be imputed simply to create a balanced panel.

Table 13.1: Statistical and econometric analysis families and principal safeguards.

Analysis family	Data structure	Methods / outputs	Key safeguard
Descriptive profiling	All variables	N, mean, SD, median, IQR, range, CV, missingness	Establish distribution and coverage before inference
Long-term trends	Annual country/crop indicators	CAGR; indexed trends; Mann-Kendall; Sen slope	Robust trend characterization; consider autocorrelation
Structural change	Long annual series	Change-point / segmented trend where justified	Identify breaks rather than forcing one linear trend
Group comparison	Country/crop/period groups	ANOVA/ANCOVA or robust/nonparametric alternatives	Use only when design/independence assumptions fit
Repeated observations	Country-year/crop-year outcomes	Mixed-effects models / generalized mixed models	Accounts for repeated measurements and hierarchical structure
Panel econometrics	Country-year or country-crop-year panels	Fixed effects / random effects; robust/clustered or Driscoll-Kraay SE where justified	Control time-invariant heterogeneity; diagnose serial/cross-sectional dependence
Model selection	Panel models	Hausman or substantive/model-based choice; information criteria where appropriate	Avoid mechanical method selection
Climate-yield models	Yield or yield anomaly	Panel/mixed regression with rainfall/temp/drought and lags/nonlinear terms	Agronomic timing and irrigation interactions matter
Time-series econometrics	Pakistan national series	Stationarity tests; ARDL/ECM/cointegration only if assumptions/data support	Avoid spurious regression in nonstationary series
Forecasting	Selected annual/monthly variables	ETS/ARIMA or other validated models; backtesting	Use for short/medium-term statistical forecasts, not deterministic futures
Multivariate structure	Standardized country/crop indicators	PCA; biplots; factor interpretation	Identify correlated dimensions; report loadings and explained variance
Typology / clustering	Country/crop profiles	Hierarchical clustering / k-means with stability checks	Identify empirical groups, not normative rankings
Efficiency	Comparable input-output systems	DEA and/or stochastic frontier if data quality supports	Estimate relative technical/economic efficiency; sensitivity essential
Trade concentration	Partner-country trade shares	HHI and diversification metrics	Supply/export market concentration
Preservation studies	Storage/coating/processing evidence	ANOVA/mixed models/meta-analysis/evidence synthesis as design permits	Commodity-specific treatment effects and uncertainty
Food-loss scenarios	Loss estimates + prices + water productivity	Deterministic ranges + Monte Carlo/sensitivity	Avoid false precision from uncertain loss percentages
Future scenarios	2030/2040/2050	Scenario accounting; uncertainty bands; sensitivity / Monte Carlo	Scenario, not prediction; assumptions explicit

13.3 Advanced Econometric Diagnostics

Where regression/econometric models are used, diagnostics address heteroscedasticity, serial correlation, multicollinearity, influential observations, residual structure and model specification. Cross-sectional dependence is tested when multi-country panels are used. Unit-root and cointegration procedures are applied only to series where non-stationarity is substantively relevant. Dynamic panel methods are considered only where the structure and endogeneity problem justifies them; they are not added simply to make the analysis appear more advanced.

13.4 Effect Sizes and Uncertainty

Statistical significance is not treated as the main measure of importance. Results emphasize effect estimates, 95% confidence intervals, practical magnitude and, where appropriate, standardized effect sizes. Multiple-comparison adjustments are made where many group contrasts are tested. Sensitivity analysis accompany estimates that depend heavily on uncertain assumptions, especially food-loss fractions, storage costs and future scenarios.

13.5 Reporting Plan

The final statistical section contains publication-class tables and concise results narratives. Tables carry self-contained titles and notes, consistent decimal precision, report exact ‘p’ values where appropriate, and include confidence intervals and effect sizes rather than relying on significance symbols alone.

Table 13.2: Planned statistical and econometric reporting outputs.

Planned table	Subject	Core contents
Table 13.1	Data coverage and descriptive statistics	N, years, mean, SD, median/IQR, min-max, missingness
Table 13.2	2000-2025 trend evidence	Mann-Kendall tau, p, Sen slope, 95% CI, CAGR
Table 13.3	Pakistan vs comparator adjusted contrasts	Estimated marginal means/contrasts, CI, adjusted p, effect size
Table 13.4	Crop productivity panel model	Coefficient, SE, 95% CI, p, standardized effect; FE/RE diagnostics
Table 13.5	Water-productivity model	Predictor effects, interactions, model fit, robust SE
Table 13.6	Climate-yield models	Lagged/nonlinear climate coefficients and uncertainty
Table 13.7	PCA / multivariate structure	Loadings, communalities if used, explained variance
Table 13.8	Country/crop cluster profiles	Centroids/medians and stability/silhouette evidence
Table 13.9	Efficiency analysis	Relative efficiency estimates and sensitivity results
Table 13.10	Food-trade/economic models	Import/export, FX/price relationships and diagnostics
Table 13.11	Preservation/storage evidence	Treatment effects, shelf-life extension, loss reduction, cost/energy
Table 13.12	Scenario results	Baseline vs scenarios; ranges/CI; food, water and economic outcomes

13.6 Completed Climate-Yield Econometric Evidence

The current formal climate-yield analysis supports a more nuanced interpretation than simple annual climate correlations. In the pooled crop fixed-effects model with crop-specific trends, annual temperature and precipitation standardized predictors are not statistically significant. Seasonal models, however, identify timing-sensitive associations: SON temperature, JJA precipitation and SON precipitation remain significant after false-discovery-rate adjustment in the pooled seasonal specification, while DJF precipitation is nominally significant but does not survive the same adjustment. Crop-specific models identify particularly strong potato associations with DJF/MAM temperature and MAM precipitation. These estimates are associative rather than causal: the sample contains only 18 annual clusters and all crops share national climate exposure.

Specification reconciliation. The pooled seasonal figure and crop-specific estimates represent distinct specifications and, where relevant, distinct multiple-testing treatments. Figure 13.1 displays intervals overlapping zero and consequently does not substantiate a statistically reliable pooled seasonal climate effect. Any reported crop-specific association is conditional on its precise model, sample and multiplicity adjustment; it must not be interpreted as a causal climate-yield effect or as confirmation of the pooled model. Numerical estimates and figure labels remain subject to chart-to-model reconciliation.

Table 13.3: Selected current climate-yield model results.

Model term	Coefficient / approximate effect	p	BH-FDR q	Interpretation
Annual temperature (pooled)	0.00218	0.665	-	No detectable annual-average association
Annual precipitation (pooled)	-0.00123	0.813	-	No detectable annual-average association
SON temperature (seasonal pooled)	+0.01366 (~+1.38% / 1 SD)	0.0059	0.0235	FDR-supported positive association
JJA precipitation (seasonal pooled)	-0.01862 (~-1.85% / 1 SD)	0.0038	0.0235	FDR-supported negative association
SON precipitation (seasonal pooled)	+0.01159 (~+1.17% / 1 SD)	0.0117	0.0311	FDR-supported positive association
Potato MAM temperature	+0.08357	<.001	0.0008	Strong crop-specific association
Potato MAM precipitation	+0.07938	0.0013	0.0138	FDR-supported crop-specific association

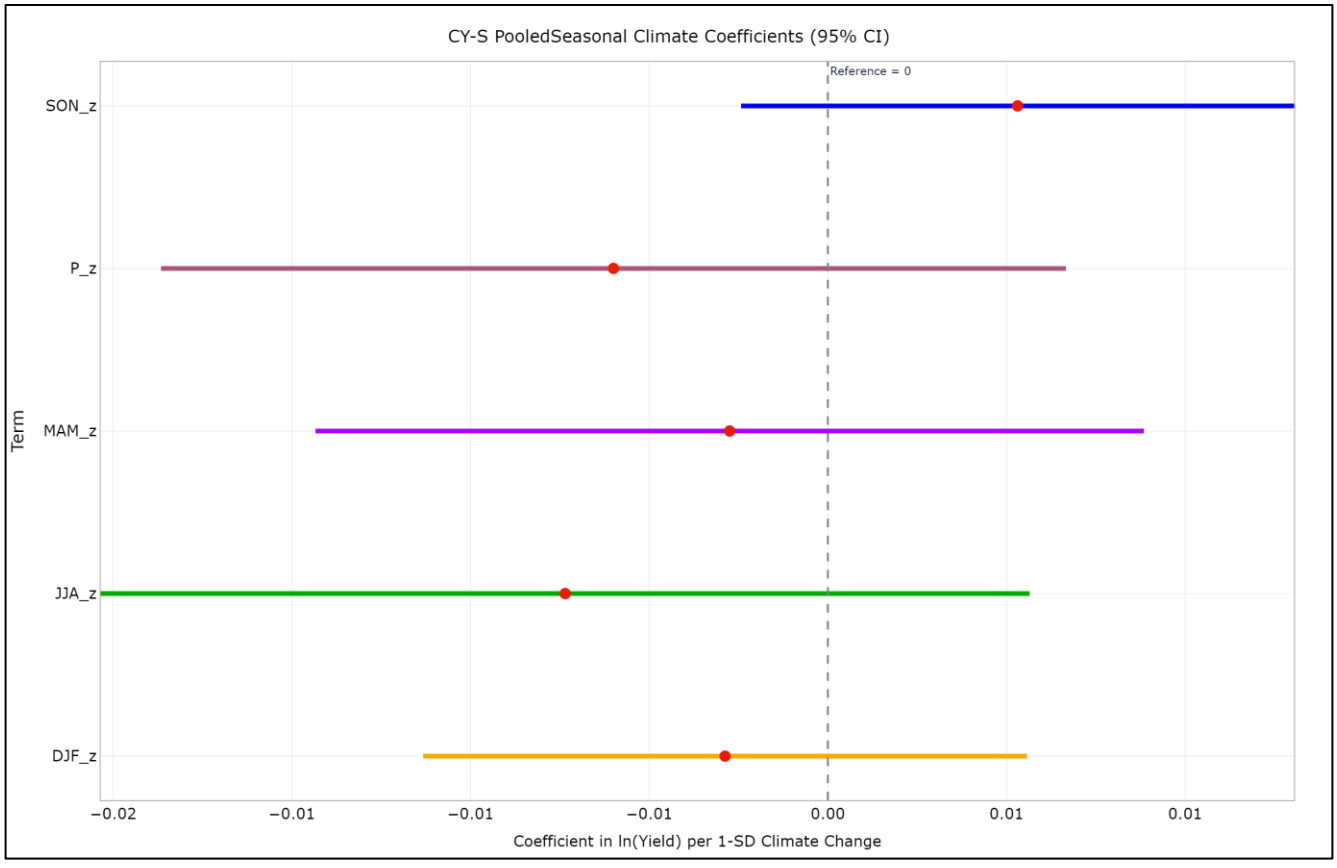


Figure 13.1: Pooled seasonal climate-yield associations from the CY-S sensitivity model (coefficients and 95% intervals).

Verification note: *All five displayed 95% confidence intervals overlap zero; the pooled sensitivity model does not establish a statistically significant climate coefficient in this specification.*

Interpretation: *In the CY-S pooled seasonal sensitivity model, the displayed standardized climate coefficients have confidence intervals that overlap zero. This does not exclude crop-specific heterogeneity, which is examined separately in Figure 13.2. These are associative estimates using a common national climate exposure and not causal estimates. DJF, MAM, JJA and SON are abbreviations of months (SON=Sep/Oct/Nov and so on).*

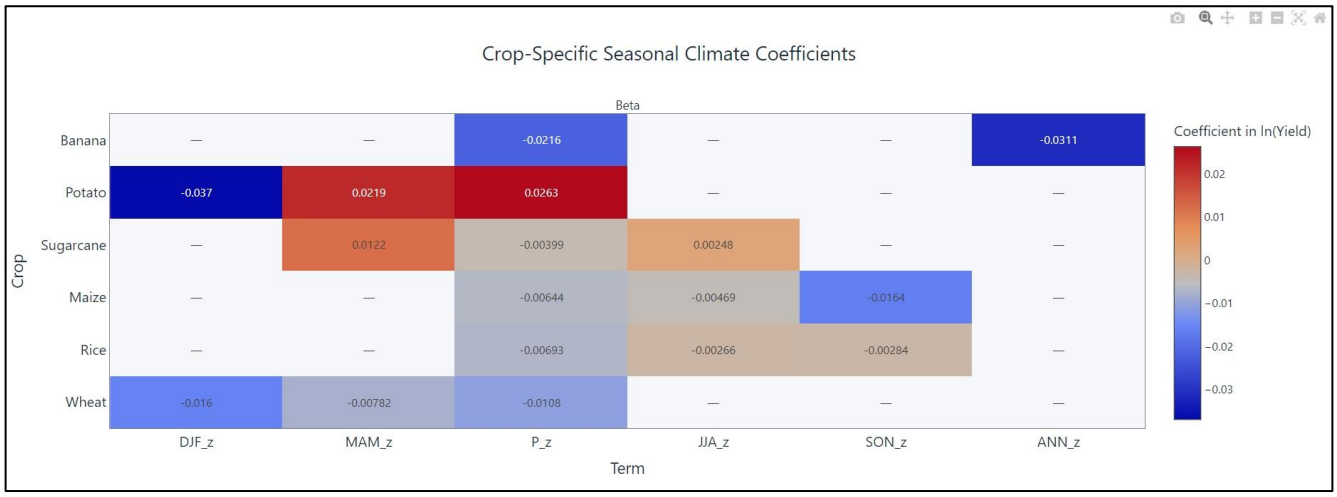


Figure 13.2: Crop-specific seasonal climate associations; the FDR-adjusted comparison threshold is q < 0.05 (no displayed coefficient meets this threshold).

Source: Author econometric analysis of Pakistan crop yields and selected standardized seasonal-climate covariates, 2007-2024. Coefficients express associations with log yield; an asterisk denotes FDR-adjusted q < 0.05. Blank cells indicate covariates not estimated for the relevant crop. These screening models do not establish causality.

Verification note: *None of the seventeen plotted terms meets the Benjamini-Hochberg threshold q < 0.05. Nominal p-values and raw confidence intervals are not evidence of significance after the stated multiple-comparison adjustment.*

Interpretation: *Crop-specific climate sensitivity is heterogeneous. No crop-specific coefficient survives Benjamini-Hochberg false-discovery-rate correction at q < 0.05 in the chart-ready model results; nominal associations, including selected potato terms, remain exploratory, whereas most crop-season terms are not statistically distinguishable from zero after multiple-testing adjustment; this argues against one national climate-response coefficient for all crops.*

13.7 Demographic, Trade and Energy-Exposure Analytics

A second econometric block now quantifies historical trends in crop productivity, food-trade exposure, wheat prices and macroeconomic scale using the same transparent specification for comparability: OLS with an intercept on the natural logarithm of the outcome, Year as the predictor and HAC/Newey-West standard errors with two lags. These models estimate average historical rates of change; they do not identify the causes of those changes.

The crop-yield results are uniformly positive over the available 2007-2024 panel: wheat about 1.08% per year, rice 1.10%, maize 4.23%, sugarcane 2.09%, potato 1.89% and banana 7.21% per year. Banana has fewer observations and therefore requires additional caution. For wheat, the independent model verification reproduced the reference coefficient (beta = 0.0107007), HAC standard error, confidence interval and model diagnostics for 18 observations, providing a direct software-validation bridge between the independent calculations and the publication workflow.

Trade and price trends show a different pattern. Total edible-oil import quantity rises by about 3.38% per year, while the nominal PKR import bill and nominal unit value rise by about 13.48% and 9.77% per year, respectively. Nominal wheat wholesale prices rise by about 10.02% per year, whereas the analyzed inflation-adjusted wheat wholesale series has an estimated trend of only about 0.68% per year and is not statistically significant (p about.35). The latter

result is retained with an explicit caveat that the CPI-based deflation method has not yet been independently source-audited.

The macroeconomic trend models are contextual rather than welfare models. Pakistan population rises at an estimated 1.98% per year over 2000-2025. Current-US-dollar GDP and GDP per resident rise at about 5.96% and 3.90% per year, respectively, but these are current-dollar trends that incorporate price and exchange-rate effects and must not be reported as real economic growth. The demographic result is relevant to food-system planning because sustained population growth increases the scale of future demand even where crop yields improve.

Table 13.4: Source-calibrated economics/econometrics trend register for independent model validation.

Series	Period / N	Estimated annual trend	Inference / guardrail
Wheat yield	2007-2024 / 18	+1.076%	Positive HAC trend; independently checked.
Rice yield	2007-2024 / 18	+1.096%	Positive HAC trend; association only.
Maize yield	2007-2024 / 18	+4.231%	Strongest common-panel crop-yield trend.
Sugarcane yield	2007-2024 / 18	+2.095%	Positive HAC trend; association only.
Potato yield	2007-2024 / 18	+1.892%	Positive HAC trend; association only.
Banana yield	2007-2024 / 14	+7.209%	Fewer observations; interpret cautiously.
Edible-oil import quantity	2006-2024 / 19	+3.382%	Physical import exposure increased.
Edible-oil nominal bill	2006-2024 / 19	+13.483%	Nominal PKR; includes price/FX effects.
Edible-oil nominal unit value	2006-2024 / 19	+9.770%	Nominal PKR/t; not a pure world-price measure.
Wheat wholesale nominal	2007-2024 / 17	+10.018%	Nominal price trend.
Wheat wholesale real	2007-2024 / 17	+0.678%, p≈.35	Not statistically significant; CPI basis unaudited.
Population	2000-2025 / 26	+1.983%	Demographic demand context.
GDP current USD	2000-2025 / 26	+5.961%	Current USD; not real growth.
GDP per resident current USD	2000-2025 / 26	+3.900%	Current USD; not income distribution.

Source / method: Historical Pakistan crop, edible-oil trade, wholesale-price and macroeconomic series, harmonized and independently cross-checked for this study. Specification: $\ln(y) = \alpha + \beta\ Year$; OLS with HAC/Newey-West standard errors (maximum lag 2). Annual percentage trend = $100[\exp(\beta) - 1]$.

13.8 Econometric Results Register and Additional Model Eligibility

The 14 historical trend models were checked against independently calculated reference estimates using harmonized annual observations, documented variable definitions and consistent estimation settings. Model inputs, specification choices, validation comparisons and diagnostic outputs remain part of the research audit trail. This independent cross-check is distinct from asserting that all raw source series have been externally verified.

The formal completed results retained in Table 13.3 and the accompanying B17 outputs are the current empirical econometric evidence. The pooled annual model does not identify significant annual temperature or precipitation associations; the pooled seasonal model reports FDR-supported SON temperature, JJA precipitation and SON precipitation associations. Crop-specific results include potato MAM temperature and MAM precipitation. The 18-year annual crop window limits power and cluster-robust inference. Seasonal findings are associative and cannot be converted into policy-effect estimates.

The remaining work is separated into three evidence-readiness groups. Completed and reproducible now: harmonized Pakistan crop, food-trade, wheat-price, population and macroeconomic trend models, together with existing climate-yield evidence, observed BACI 2024 food/agriculture trade context, the six-crop representative farm-economics screening and AG01-AG03 discounted-cash-flow screening. Scenario-ready now, conditional on documented assumptions: post-harvest loss reduction, water-productivity improvement, preservation/storage investment and irrigation/water-value sensitivity. Not yet eligible for national causal or nationally representative profitability claims: farm-margin generalization beyond the representative screening cases, verified full-life project economics, and broader nutrition/affordability regressions where matched source years and cost data remain incomplete.

Results-reporting convention. Every completed model must carry a dataset/sheet identifier, unit of analysis, period, number of observations and clusters, dependent-variable transformation, predictors, estimator, robust-standard-error choice, model-fit measures, diagnostics, confidence intervals, unadjusted p values and multiple-testing adjustment when applicable. Descriptive associations, model-based estimates and conditional scenarios appear under distinct labels.

The new cross-country block is principally a latest-available snapshot and not treated as a balanced 2000-2025 panel. Primary outputs are GDP-anchored two-panel comparators, country rankings, choropleths, bubble/relationship charts and transparent coverage tables. Demographic measures include fertility, age shares, dependency/support ratios and youth-to-old structure; financial measures include merchandise trade, broad fuel-bill/earnings proxies, reserves and current-account balance; physical energy measures include oil/gas production, consumption, domestic coverage and apparent import dependency.

Three safeguards are mandatory. First, oil and gas display in MMbbl/d and MMscf/d where available, with original TWh retained. Second, fuel-dollar proxies must remain labelled as proxies because they apply broad fuel shares to merchandise trade rather than reconstructing every customs line. Third, exact-HS hydrocarbon totals must carry the component-count/coverage flag: missing HS2709, 2710, 271111 or 271121 components cannot be silently interpreted as zero. Mixed-year and near-year calculations retain their alignment status in tables, captions and hover text.

13.9 Consolidated Economics and Econometrics Results

The final economics register combines observed historical outcomes, econometric trend estimates, representative farm screening and illustrative multi-year investment cases. These evidence classes are intentionally kept separate. 'Observed' describes measured historical values or accounting identities; 'Econometric' describes model-based historical associations with the stated diagnostics; 'Representative screening' applies sourced but non-national farm inputs to comparable analytical cases; and 'Illustrative DCF' validates project-economics logic under stated assumptions. The latter two categories must not be presented as national realized profitability or investment performance.

Table 13.5: Consolidated economics/econometrics results and evidence-status register.

Domain	Metric / case	Quantitative result	Evidence class	Interpretation / guardrail
Crop trends	Wheat yield	+1.076%/yr	Econometric	Positive HAC historical trend; association, not cause.
Crop trends	Rice yield	+1.096%/yr	Econometric	Positive historical trend; residual-normality caveat retained.
Crop trends	Maize yield	+4.231%/yr	Econometric	Strong positive historical trend.
Crop trends	Sugarcane yield	+2.095%/yr	Econometric	Positive historical trend.
Crop trends	Potato yield	+1.892%/yr	Econometric	Positive historical trend.
Crop trends	Banana yield	+7.209%/yr	Econometric	Strong trend with shorter N=14 series.
Food trade	Edible-oil import quantity	+3.382%/yr	Econometric	Physical import exposure increased.
Food trade	Edible-oil nominal bill	+13.483%/yr	Econometric	Strong nominal growth; serial-correlation caveat; includes price/FX effects.
Food trade	Edible-oil nominal unit value	+9.770%/yr	Econometric	Strong nominal trend; persistent residuals; not a pure world-price measure.

Domain	Metric / case	Quantitative result	Evidence class	Interpretation / guardrail
Food trade	Edible-oil bill bridge	PKR +787.5bn; 26.7% quantity / 73.3% unit value	Observed/accounting	Accounting decomposition, not causal attribution.
Food trade	BACI food/ag trade 2024	Exports ~$8.63bn; imports ~$8.46bn; balance +~$0.175bn	Observed	Calendar-year BACI sector aggregation; not interchangeable with PBS fiscal-year accounts.
Prices	Wheat nominal wholesale	+10.018%/yr	Econometric	Strong nominal price trend; serial-correlation caveat.
Prices	Wheat real wholesale	+0.678%/yr; not significant	Econometric	No statistically significant long-run real-price trend in analyzed series; CPI basis caveat.
Macro	Population	+1.983%/yr	Econometric/context	Demographic demand baseline; simple trend has serial-correlation/nonlinearity caveats.
Macro	GDP current USD	+5.961%/yr	Econometric/context	Current-dollar trend; must not be reported as real GDP growth.
Macro	GDP per resident current USD	+3.900%/yr	Econometric/context	Current-dollar per-capita trend; not a distributional welfare measure.
Farm screening	Banana	Net -$155.0k; BCR 0.40; yield 11.60 vs BE 29.20 t/ha	Representative screening	Strongly negative under current regional/proxy inputs; not a national banana-profitability estimate.
Farm screening	Maize	Net +$75.7k; BCR 4.50; yield 5.93 vs BE 1.32 t/ha	Representative screening	Strongly positive; cost evidence requires explicit sensitivity.
Farm screening	Potato	Net +$225.0k; BCR 5.29; yield 24.90 vs BE 4.70 t/ha	Representative screening	Strongly positive; mixed input vintages/regions limit generalization.
Farm screening	Rice	Net -$0.3k; BCR ~1.00; yield 2.71 vs BE 2.72 t/ha	Representative screening	Approximately break-even; highly sensitive to small changes.
Farm screening	Sugarcane	Net +$10.9k; BCR 1.05; yield 74.24 vs BE 70.66 t/ha	Representative screening	Marginally positive; cost split partly inferred.
Farm screening	Wheat	Net -$2.6k; BCR 0.97; yield 3.27 vs BE 3.36 t/ha	Representative screening	Slightly below break-even; plausible price/cost changes can reverse result.
Project screening	AG01 wheat storage	NPV +$221.5k; IRR 24.40%; DPB 5.06 y	Illustrative DCF	Positive under assumed scale/loss/value/CAPEX/OPEX; not realized project evidence.
Project screening	AG02 rice drying	NPV -$103.6k; IRR 7.19%; DPB not reached	Illustrative DCF	Does not clear 12% base hurdle.
Project screening	AG03 irrigation recovery	NPV -$74.3k; IRR 9.13%; DPB not reached	Illustrative DCF	Does not clear 12% base hurdle; water value and recoverability are decisive.

Source / preparation note: consolidated from the verified econometric reports, observed trade/accounting tables and final Agricultural & Food Economics screening outputs. Farm values are shown on the common 100-ha analytical scale. DPB = discounted payback. All model and evidence-status caveats remain part of the reported result.

Integrated interpretation: *Five conclusions are supported at the current evidence level. First, major-crop yields have generally improved, but yield growth and farm profitability are not the same outcome. Second, edible-oil import pressure is both physical and financial, with nominal unit-value change accounting for the larger share of the endpoint bill increase. Third, nominal wheat-price escalation is not mirrored by a statistically significant long-run trend in the available inflation-adjusted price series. Fourth, preservation and irrigation interventions can generate physical benefits yet fail an investment hurdle once CAPEX, OPEX and discounting are included. Fifth, the farm and project screens remain conditional: the direction and magnitude of profitability can change when local prices, input costs, water requirements, post-harvest losses, utilization and financing conditions change.*

13.10 Full Model-Level OLS Diagnostics and Independent-Use Restrictions

Fourteen complete OLS diagnostic analyses were reviewed for this synthesis: six crop-yield series; edible-oil import quantity, nominal bill and unit value (T_Q, T_B, T_U); nominal and inflation-adjusted wheat wholesale prices (P_N, P_R); and three macroeconomic series (M_G, M_P, M_PC). These model-level OLS diagnostics must be distinguished from the HAC/Newey-West trend estimates reported in Table 13.4. The two analyses differ in inference procedure, and their diagnostics are not interchangeable.

Inference boundary. Conventional OLS residual tests diagnose potential misspecification; they are not interchangeable with HAC/Newey-West trend inference. Serial correlation, heteroskedasticity, influential years, short samples and trend-related nonstationarity can affect uncertainty estimates. Accordingly, slope estimates are used as descriptive historical summaries. A statistically significant time coefficient must not be interpreted as causal evidence of climate, policy or technology effects.

Table 13.6: Complete-report diagnostics for the 14 individual OLS trend models (source-reported).

Series	N	R^2	DW	BP p	White p	RESET p	BG p	JB p
M_G	26	0.925	0.376	0.860	0.335	0.000	0.000	0.334
M_P	26	0.988	0.078	0.182	0.319	0.000	0.000	0.529
M_PC	26	0.870	0.458	0.719	0.429	0.000	0.000	0.395
P_N	17	0.848	0.523	0.063	0.056	0.259	0.004	0.586
P_R	17	0.079	0.871	0.372	0.318	0.315	0.034	0.659
T_B	19	0.845	0.576	0.188	0.069	0.721	0.006	0.413
T_Q	19	0.768	1.749	0.089	0.103	0.364	0.787	0.180
T_U	19	0.735	0.372	0.354	0.624	0.521	0.001	0.395
banana	14	0.945	1.730	0.183	0.228	0.598	0.703	0.627
maize	18	0.960	1.724	0.075	0.148	0.808	0.793	0.329
potato	18	0.594	2.507	0.051	0.124	0.648	0.260	0.569
rice	18	0.646	2.356	0.399	0.680	0.300	0.351	0.015
sugarcane	18	0.892	1.670	0.632	0.160	0.076	0.915	0.740
wheat	18	0.718	2.190	0.343	0.032	0.343	0.270	0.604

DW = Durbin-Watson; BP = Breusch-Pagan; BG = Breusch-Godfrey; JB = Jarque-Bera. Small test p-values flag possible diagnostic violations, not causal effects. Diagnostics are unadjusted source-report tests and may be unstable for the short crop-year samples. A high R^2 in trending annual levels does not validate causal inference; residual dependence, heteroskedasticity, non-stationarity, model selection and multiple testing remain substantive concerns.

Table 13.7: Influence and model-fit supplement from complete Brill-Viz regression PDFs.

Model	Adjusted R^2	Max Cook D	Influential rows > 4/N
M_G	0.9222	0.2154	2
M_P	0.987	0.318	2
M_PC	0.8642	0.225	2
P_N	0.8375	0.3962	2
P_R	0.01745	0.2679	2
T_B	0.8361	0.3748	2
T_Q	0.7544	0.6466	1
T_U	0.7192	0.2409	1
banana	0.9398	0.3846	1

maize	0.957	0.4742	2
potato	0.5688	0.4104	1
rice	0.6239	0.4482	2
sugarcane	0.8851	0.4821	3
wheat	0.6999	0.3838	3

No country-level geographic regression, causal identification, locally measured farm economics or empirically calibrated 2030-2050 forecasts are established merely by these reports. Wherever models fail at least one residual diagnostic, emphasize descriptive association, seek heteroskedasticity/autocorrelation robust estimation and test sensitivity before policy attribution.

14. Integrated Quantitative Synthesis and Publication Outputs

The integrated evidence supports a selective, reproducible set of descriptive comparisons and economics/econometrics findings. Figures are included only where their source observations, geographic coverage, years, units and transformations can be described transparently. Potential future visualization counts are not themselves scientific findings; geographic comparisons require country-level source concordance and explicit treatment of missing observations.

Table 14.1. Updated publication-output families and target ranges.

Output family (updated rough target)	What it includes
General analytical charts (70-90)	Production, yield, crop area, climate/rainfall, population, WASH, food trade, macro-financial exposure, energy dependence, water/irrigation and productivity
Regional / international comparative charts (25-35 of the above)	Pakistan vs functional peers and global context; water, agriculture, crops, rainfall, demography, GDP/trade and energy exposure
Formal statistical/econometric tests & model outputs (40-55)	Trend tests, breaks, correlations, FDR, FE/HAC/mixed/panel models and robustness checks
Statistical/econometric visualizations (25-35)	Coefficient/forest plots, heatmaps, residuals, breakpoints, uncertainty and distributions
Economic/econometric analyses (25-35)	Real prices, food/fuel import burden, external balance, substitution, preservation economics, water value and scenarios
Country/regional choropleths (~15-20)	Water, agriculture, crop, population, fertility/age structure, GDP/trade, fuel/energy exposure and rainfall maps from tabular country data
Specialist Pakistan GIS maps (10)	Spatial irrigation, WASH, basin, WaPOR/productivity and hotspot products
Integrated dashboards / synthesis figures (10-15)	Water-food-climate-trade-demography-energy-risk, comparator scorecards, scenario/evidence synthesis
Main-thesis unique visual exhibits (~100-125)	Carefully selected figures, maps and synthesis visuals; overlapping categories not double-counted
Appendix / supplementary figures (30-50)	Diagnostics, alternate models, secondary country/crop views and supporting maps

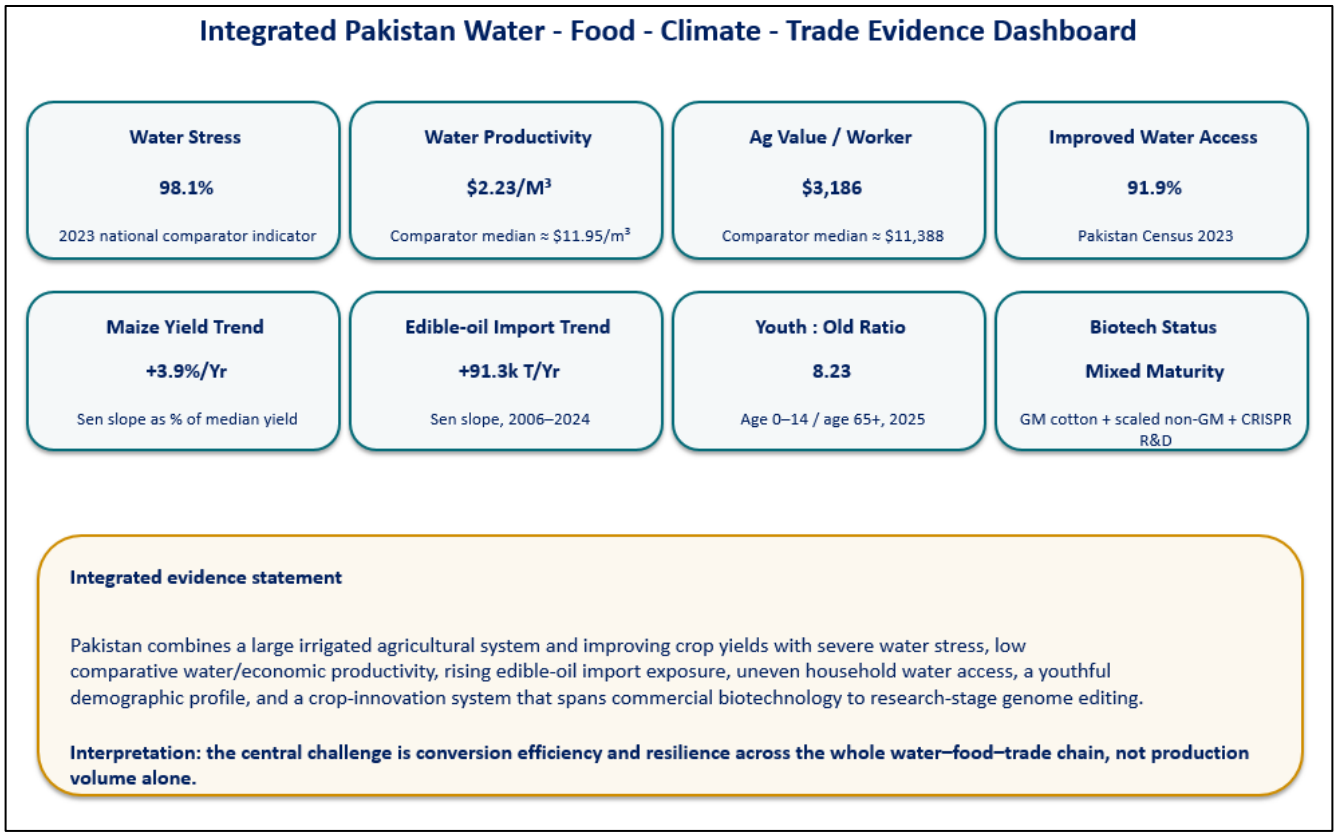


Figure 14.1: Integrated Pakistan water-food-climate-trade evidence dashboard.

Interpretation: *The integrated evidence does not point to one isolated failure or one isolated solution. Pakistan combines improving biological productivity with severe water pressure, low comparative resource/economic productivity, import exposure, spatial WASH inequality, demographic demand pressure and a mixed-maturity innovation system; the economics and scenario pass therefore needs to evaluate packages of interventions rather than single-variable solutions.*

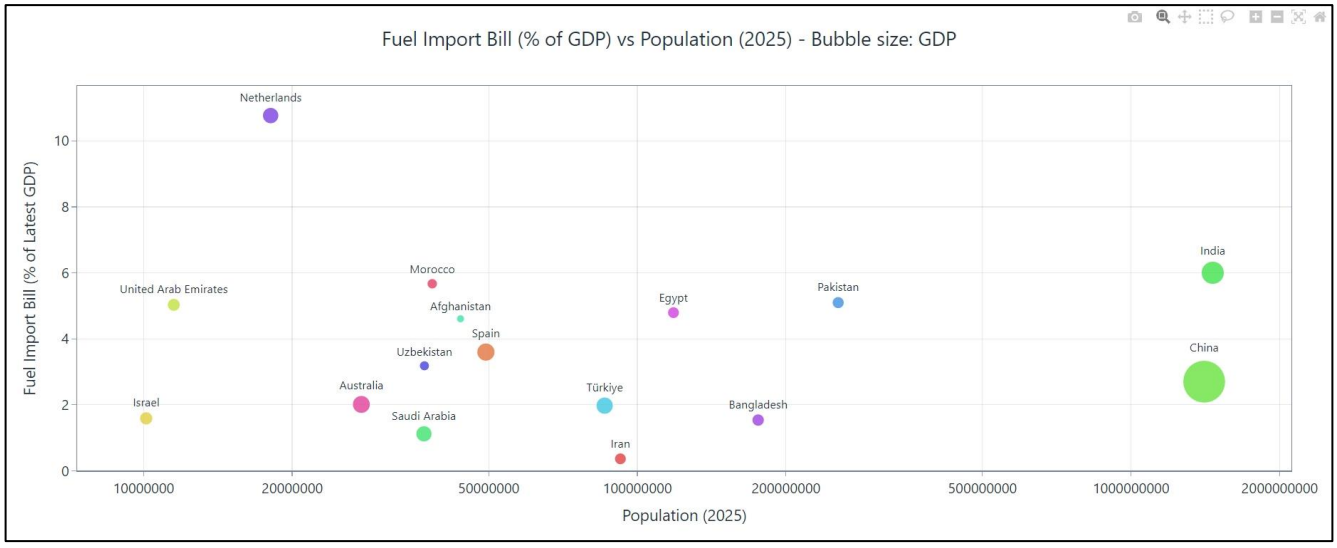


Figure 14.2: Demographic scale and fuel-import financial pressure across countries.

Evidence boundary: *Country points span differing observation years and include fuel exposure proxies. Bubble position and relative size are exploratory, not a harmonized global ranking.*

Interpretation: *Demographic scale and external energy pressure are distinct dimensions. Large populations create large absolute food and infrastructure requirements, but the financial burden of imported fuel depends on income, domestic energy supply, trade structure and GDP. Pakistan combines very large demographic scale with a fuel-import proxy near 5% of GDP, making energy-cost sensitivity relevant to irrigation, fertilizer, transport and cold-chain scenarios.*

15. Future Water-Food-Economic Scenarios: 2030/2040/2050

This chapter identifies conditional pathways for 2030, 2040 and 2050 rather than presenting validated numerical forecasts. The historical 2000-2025 and crop/economics analyses support the selection of intervention themes-water and crop productivity, groundwater management, post-harvest retention, trade resilience, demographic demand and energy-related operating costs-but do not yet quantify integrated national outcomes at all three horizons. Quantitative scenarios require explicit baselines, calibrated assumptions, linked demand/supply and investment equations, uncertainty bands, and sensitivity testing. Until that work is completed, the timelines are strategic planning horizons, not evidence that any stated 2030/2040/2050 target can be achieved.

Table 15.1: Scenario framework for 2030, 2040 and 2050.

Scenario	Core assumption	Primary outcomes
S0 Baseline / reference	Observed productivity and loss trends continue under demographic/climate assumptions	Food supply-demand balance; water demand; import exposure
S1 Irrigation efficiency	Improved delivery/application efficiency and/or water productivity	Water requirement; output; value/m3
S2 Yield-gap reduction	Feasible productivity gains relative to historical and comparator evidence	Production, land pressure, imports
S3 Post-harvest loss reduction	Commodity-specific loss reductions from storage/cold-chain/processing	Food retained; USD retained; embedded water retained
S4 Crop-mix/value optimization	Constrained shift toward higher food/economic water productivity	Food/nutrition, value/ha, value/m3, trade
S5 Groundwater constraint	Limits on unsustainable groundwater abstraction	Production risk and substitution needs
S6 Climate stress	Higher heat/drought/water stress based on climate projections	Yield, water demand, food gap
S7 Integrated resilience	Combination of evidence-supported productivity, storage, water and value-chain measures	Water security + food security + economic value
S8 Preservation infrastructure	Silos, hermetic storage, pre-cooling, cold chain, processing and packaging	Avoided losses, capex/opex, energy, BCR/NPV
S9 Demographic demand & diet transition	Alternative population/age-structure and income-linked food-basket assumptions	Food quantity/composition, water demand, cold-chain/storage demand, import requirements
S10 Energy / external-cost shock	Higher imported fuel/energy prices and/or exchange-rate pressure	Pumping, fertilizer/logistics/cold-chain costs, food prices, import bill and investment viability

Scenario interpretation: *The pathways distinguish (i) 2030 near-term efficiency, loss reduction and data/implementation priorities; (ii) 2040 structural irrigation, storage, crop-mix and productivity investment choices; and (iii) 2050 long-horizon groundwater, climate, food-demand and resource-resilience stress tests. These are proposed intervention sequences, not calibrated forecasts or proven policy impacts. Future models must assess trade-offs and downside cases, including financing and energy/import-cost shocks, before assigning numerical benefits to individual pathways.*

16. Analytical Propositions to be Tested

Several propositions can now be sharpened using completed descriptive and inferential evidence. They remain propositions where causal or advanced spatial/economic confirmation is still pending.

- Pakistan's high irrigation intensity coexists with low comparative whole-economy water productivity and agricultural value added per worker; crop-specific consumptive-water productivity remains to be quantified through the WaPOR/economic extension.
- The comparator evidence indicates large international differences in water and economic productivity, while Pakistan's crop panel shows strong but uneven yield gains; the next stage must connect these gains to crop-specific water use and value.
- Groundwater dependence provides short-run reliability in many irrigated areas but may create long-run sustainability risk where abstraction exceeds recharge or water quality deteriorates.
- Post-harvest loss reduction can improve food availability without requiring proportional increases in land or irrigation water, but the magnitude is commodity- and supply-chain-specific.
- Cold-chain and modern storage investment is economically attractive for some commodities and locations but not universally; utilization, energy cost, market access and loss reduction determine viability.
- Edible-oil import dependence is a material and statistically rising food-system/foreign-exchange exposure; domestic substitution needs to nevertheless be evaluated against water, land, yield, cost and trade-off constraints.
- Trade diversification and value addition can improve resilience, yet export expansion must be interpreted jointly with domestic availability and water opportunity cost.
- Provincial WASH differences already show that national averages conceal important spatial inequality; irrigation, groundwater and crop-water-productivity mapping tests the same proposition for agricultural water security.
- An integrated package of productivity, genetic/breeding innovation, preservation and water-management improvements may outperform isolated interventions, but benefits, costs, adoption constraints and uncertainty must be quantified rather than assumed.
- Pakistan's innovation system already contains commercially deployed biotechnology and scaled non-GM breeding technologies alongside a larger research-stage genome-editing pipeline; translation from research to approved and widely adopted farm practice is therefore a key analytical bottleneck rather than a binary 'has/has-not biotechnology' question.
- Pakistan's youthful age structure implies sustained future food, water and employment demand, but a demographic dividend cannot be assumed; it depends on human-capital investment, job creation and productivity growth.
- Pakistan's broad fuel-import bill proxy is about 5.1% of GDP and its fuel net-import pressure proxy about 5.0% in the latest completed cross-section, above the core-comparator median for net-import pressure; this supports testing energy-price and exchange-rate sensitivity across irrigation, fertilizer, logistics and cold-chain economics, without implying a causal effect from the snapshot alone.

16.1 Consolidated Conclusions and Implications

Across its historical, spatial, trade and socioeconomic components, the synthesis identifies food security as a conversion-and-retention challenge: production growth matters, but it cannot be evaluated independently of water stress, market access, purchasing power, post-harvest losses and resilience.

The six observed crop-yield histories generally trend upward, although regressions in annual trending series are descriptive and not causal. Comparative productivity conclusions depend on harmonized commodity definitions, years, denominators and actual country coverage; conceptual maps and sparse choropleths cannot replace complete measured spatial comparisons.

The edible-oil accounting bridge illustrates that a growing nominal import bill reflects both higher physical quantities and changes in unit values. It is not a causal decomposition of international prices, exchange rates or domestic policy. Similarly, nominal wheat-price escalation cannot establish a corresponding increase in inflation-adjusted affordability pressure unless the deflator and price-series provenance are verified.

Farm-model margins for banana, maize, potato, rice, sugarcane and wheat, and project appraisals for AG01-AG03, are conditional calculations on the selected prices, costs, yields, loss or water-recovery factors and financial parameters. They demonstrate sensitivities and decision thresholds; none supports a nationally representative farm-profitability ranking or a project investment recommendation.

Policy implications therefore emphasize measurable water and farm productivity, better storage and preservation, trade resilience and improved information systems. Priority next steps are harmonized country- and district-level observations, actual farm/project cost and revenue records, measured water withdrawals and recoveries, and documented uncertainty. The present release can inform the direction of inquiry but does not claim to resolve these evidence gaps.

17. Evidence Readiness and Research Priorities

The research provides a broad baseline across national crops, climate, irrigation, food trade and prices, WASH, demographic structure and international comparators. Coverage differs among indicators and years, and the completeness of the analytical compilation should not be mistaken for full source verification or empirical validation of farm and investment economics. The remaining work is targeted: verify selected graphics, document source definitions, reconcile econometric specifications, obtain matched microeconomic observations where feasible, and calibrate future scenarios before quantitative forecasting.

Table 17.1: Current analytical readiness and remaining workstreams.

Workstream	Current readiness	What is already usable	Primary remaining gap
Literature / source architecture	~95%	Source-first framework, major evidence families and provenance rules	Ongoing source updates and final bibliography normalization
National crops / climate	~90-100%	2000-2025 macro-climate; formal 2007-2024 crop panel; trend/breakpoint results	Additional commodity breadth and 2025 crop updates where released
Water / international comparators	~90%	16-country water/agriculture benchmark plus demography/rainfall context	Crop-specific consumptive-water productivity and some historical harmonization

Workstream	Current readiness	What is already usable	Primary remaining gap
Trade / prices / economics	~95%	Edible-oil/wheat evidence; 199-country merchandise trade; broad fuel-exposure proxies; current account/reserves; oil/gas dependency context	Full food-trade basket, exact-HS energy completion and deeper causal/time-series econometrics
WASH	~95%	2023 provincial/territory summary and GIS-ready logic	District-level mapping/joins where required
Genetics / biotechnology	Evidence layer added	Pakistan maturity pipeline + global comparator evidence	Quantified adoption/outcome series where defensibly available
Visualizations / Research template	~95%	Generic choropleths, rich statistics, publication exports and connected summaries	Final figure curation and stronger synthesis-dashboard workflow
Crop-specific water productivity	~45%	Method and WaPOR pathway defined	Raster extraction, crop masks/yield joins and economic conversion
Advanced spatial econometrics	~35%	GIS package and map specifications defined	WaPOR/subnational extraction and spatial modeling
Demography / macro-financial / energy exposure	~95% for cross-sectional synthesis	211-country demographic schema; GDP 204; merchandise trade 199; fuel shares ~193-194; reserves 180; current account 196; industry-unit oil/gas metrics	Historical panel harmonization, uneven debt vintages and partial exact-HS energy components

The next research priorities are to preserve the auditable historical trend and screening record; verify remaining chart-specific data and formulas; test sensitivity to alternative farm and project inputs; document the distinction between observed, assumed and derived quantities; and calibrate any 2030/2040/2050 projections with independently assessed baseline and uncertainty ranges. These tasks refine confidence and applicability without nullifying the descriptive contribution of the present synthesis.

18. Current Limitations and Interpretation Guardrails

The present synthesis now contains a completed observed historical economics baseline, a source-referenced econometric trend register, six representative crop/farm screening cases and three internally consistent but externally unvalidated preservation/irrigation investment screens, but these layers do not all have the same evidentiary status. The farm cases use a common 100-ha analytical scale and combine observed crop yields with regional, study-specific or proxy prices, production costs, water-use requirements and post-harvest-loss assumptions. They are indicative screening cases, not nationally representative Pakistan farm-profitability estimates. Maize and potato appear strongly positive under the current inputs, rice is approximately at break-even, sugarcane is marginally positive, wheat is slightly below break-even and banana is strongly negative; each conclusion is conditional on the assumed input parameters and needs to be sensitivity-tested. AG01-AG03 remain illustrative investment scenarios until their throughput, measured loss reduction or recoverable water, local CAPEX/OPEX, utilization, energy cost, tax/financing treatment and realized price/value assumptions are replaced by verified project data. Principal remaining evidence gaps include nationally representative crop-specific cost and margin data, verified storage/cold-chain and irrigation full-life investment histories, crop-specific consumptive-water productivity, advanced WaPOR/subnational spatial analysis, complete commodity/stage food-loss evidence, intervention-level preservation effect sizes and costs, and final 2030/2040/2050 scenario calibration.

Economics reporting guardrail. No screening result in this synthesis needs to be read as an investment recommendation, national farm-income estimate or forecast of realized returns. Full economics would require matched farm/project records for the same location and period, including actual farm-gate prices, input quantities and prices, labour and land accounting, irrigation source and measured water use, taxes/subsidies, financing, replacement capital, maintenance, utilization, quality premiums/discounts, residual value and uncertainty distributions. Where the current evidence mixes regions, market levels or source years, that limitation remains part of the result rather than being hidden through false precision.

Interpretation guardrails are explicit. Cross-country correlations are ecological and non-causal. Demographic structure is context, not a welfare or policy ranking. A high fuel-import bill does not by itself imply vulnerability because export earnings, re-exports, domestic production, GDP scale and the current account differ. Broad fuel proxies must not be relabelled as exact oil/gas/LNG customs bills, and partial exact-HS totals must not treat missing components as zero. National seasonal climate-yield models have limited annual clusters and shared national exposure across crops. Pettitt breakpoints are screening signals, not proof of policy effects. Regulatory approval is not equivalent to commercial adoption, and genome-editing research is not equivalent to released farm technology.

18.1 Publication-Readiness Requirements and Release Controls

The present synthesis is suitable as an independent exploratory and comparative research publication provided the distinction between observational evidence, derived trends, illustrative assumptions and pending verification is maintained. It is not a peer-reviewed national economic assessment or a validated investment appraisal. Charts identified as pending verification must be explicitly qualified and not used as independent substantiation of numerical claims. Publication with transparent constraints is preferable to presenting screening results as established field outcomes.

Table 18.1: Publication readiness requirements.

Pre-publication check	Required action	Acceptance criterion
Figures and tables	Reconcile figure/table register to embedded objects, captions and references; remove or explicitly label proposed/unverified figures.	No unlabeled placeholder or conceptual GIS illustration is presented as measured evidence.
Data and comparators	Check numerical values, units, vintage, sources and 16-country coverage in Chapter 12; distinguish 7-country map subsets.	Every cross-country claim matches its supporting table and year/coverage note.
Economics and econometrics	Retain indicative farm/project economics caveats and distinguish observed results, derived screens and hypotheses.	No scenario NPV, IRR or trend is described as realized national performance.
2030/2040/2050 pathways	Retain directional strategic pathways; specify that fully calibrated and uncertainty-tested national scenarios are future work.	No unvalidated quantitative target is presented as a forecast.
Document finishing	Refresh contents and page numbers, captions, numbering, cross-references, references, headers/footers and final page layout.	Final rendered copy and Word file agree, with no broken fields or layout defects.
Research continuation	Identify next analytical work and reproducibility priorities separately from completed findings.	Readers can distinguish current conclusions from the Version 2.0 agenda.

18.2 Evidence-Validation Boundary and Outstanding Work

Completed within the available analytical records: model/report inventory, transfer of the principal six-crop and AG01-AG03 reported values, explicit classification of OLS diagnostics versus HAC trend inference, documentation of the edible-oil quantity/unit-value accounting bridge, and identification of figure-level reconciliation items. These are internal consistency or reporting checks; they are not source-level or field verification.

Checks still feasible with retained numerical source series: recalculate model coefficients and robust intervals from dated annual observations; audit CPI base/year and nominal versus real wheat prices; recompute import-bill decompositions; reconcile every quantitative chart with its plotted values, labels, model specification and source vintage; review country-level choropleth joins; independently recalculate cash-flow formulas and sensitivity thresholds. Until separately completed, these tasks must not be described as verified.

Not defensible with the present inputs: *regionally or nationally representative crop net returns; demonstrated storage-loss avoidance, water savings or incremental farm revenue; validated CAPEX/OPEX and actual project NPV/IRR; causal effects of climate, irrigation policy or technology adoption; district-wide or global maps lacking consistent quantitative values; and calibrated 2030/2040/2050 economic forecasts. These require new observational, administrative or field/project records rather than more model elaboration.*

Release rule: *unresolved results may be reported only as conditional scenarios or provisional illustrations, with the source year, definitions and uncertainty attached. Figures 8.3, 8.8, 9.3, 9.4, 10.3, 10.4, 10.6, 13.1, 13.2 and 14.2 remain on the chart-specific reconciliation list. Do not use these figures independently to substantiate numerical claims until their underlying values are checked.*

Editorial Statement for the Current Release

This publication represents the current stage of an ongoing independent research programme on Pakistan's water, agriculture and food-security system. It brings together the available historical, spatial, demographic, agricultural, trade, economic and international comparative evidence to identify structural constraints, documented relationships and plausible areas for action. The findings are presented at the level supported by their source data: observed trends and validated calculations are differentiated from proxy estimates, indicative economics, illustrative maps and proposed strategic pathways.

The 15-country comparator group is selected for distinct analytical functions-including regional demographic and agricultural peers, water-stressed or irrigation-relevant economies, advanced productivity and technology systems, extreme-aridity food-security approaches, and fragile-system context. Not every indicator has consistent coverage across all 16 countries including Pakistan; each substantive comparison therefore depends on documented source-year and metric comparability.

The 2030, 2040 and 2050 discussion sets out strategic directions, not a validated numerical forecast. Subsequent research will focus on complete publication figures and verified GIS extractions, comparable crop-specific and country-level water/food productivity, measured farm and project costs, trade-dependence metrics, statistical robustness, and calibrated demographic-climate-economic scenarios with explicit sensitivity and uncertainty analysis.

Publication designation: Independent Research and Analytical Synthesis (October 2026). This is a non-peer-reviewed release built on traceable but unequally complete evidence. Descriptive historical comparisons, accounting estimates and conditional economic scenarios are distinguished throughout. Model associations are non-causal; certain figures await source-level reconciliation; and national farm or project economics cannot be validated without further primary inputs.

Appendix A: Supporting Statistical and Econometric Results

The following statistical and economic calculations were prepared using Brill-Viz analytical routines and available public observations, supplemented where necessary by explicitly stated proxy and illustrative inputs. The economics are screening-level, not representative field valuations. Crop, trade and price series differ in units, reporting periods and observation counts. Time-trend models describe historical associations rather than causal effects or forecasts.

Table A.1. Observed annual crop-yield, edible-oil trade and price series: descriptive statistics.

Variable	N	Mean	SD	Median	IQR	Min	Max	Years covered
Wheat yield (t/ha)	18	2.825	0.192	2.818	0.189	2.451	3.268	2007-2024
Rice yield (t/ha)	18	2.425	0.170	2.441	0.132	2.039	2.711	2007-2024
Maize yield (t/ha)	18	4.575	1.043	4.366	1.603	3.037	6.387	2007-2024
Sugarcan yield (t/ha)	18	59.645	7.112	57.701	8.285	48.616	74.244	2007-2024
Potato yield (t/ha)	18	22.264	2.739	22.610	3.990	16.450	25.270	2007-2024
Banana yield (t/ha)	14	6.602	2.733	6.499	4.315	3.093	11.595	2007-2024
Edible-oil imports (000 t)	19	2634.417	531.761	2700.800	765.950	1695.800	3349.300	2006-2024
Edible-oil bill (PKR bn)	19	300.515	254.512	210.842	116.355	44.212	977.264	2006-2024
Wheat price, nominal (PKR/unit)	17	1598.825	1040.250	1296.833	600.199	475.833	4295.499	2007-2024
Wheat price, real (source units)	17	3589.965	476.908	3574.454	623.749	2924.725	4520.713	2007-2024

Note: N counts actual non-missing annual observations. SD is sample standard deviation (ddof=1); IQR is the 75th minus 25th percentile. Crop yield is t/ha; T_B edible-oil import bill is converted from PKR million to PKR billion (÷1,000). Other series retain their original published units; price-series definitions and fiscal/calendar treatment require reference to the named analytical variable definitions. No missing water productivity or food-import dependency values were fabricated.

Table A.2. Completed log-linear annual trend regressions (HAC standard errors).

Series / predictor	B	SE (HAC)	95% CI for B	p	Annual trend	Model / diagnostic note
Yield: Wheat	0.01070	0.00160	[0.00757, 0.01384]	<0.001	+1.08%	log(value) ~ year; HAC(2); n=18; R^2=0.718
Yield: Rice	0.01090	0.00139	[0.00818, 0.01362]	<0.001	+1.10%	log(value) ~ year; HAC(2); n=18; R^2=0.646
Yield: Maize	0.04144	0.00197	[0.03758, 0.04529]	<0.001	+4.23%	log(value) ~ year; HAC(2); n=18; R^2=0.960
Yield: Sugarcan	0.02073	0.00160	[0.01759, 0.02387]	<0.001	+2.09%	log(value) ~ year; HAC(2); n=18; R^2=0.892
Yield: Potato	0.01874	0.00271	[0.01343, 0.02405]	<0.001	+1.89%	log(value) ~ year; HAC(2); n=18; R^2=0.594
Yield: Banana	0.06961	0.00311	[0.06350, 0.07571]	<0.001	+7.21%	log(value) ~ year; HAC(2); n=14; R^2=0.944
Trade: Q	0.03326	0.00442	[0.02460, 0.04192]	<0.001	+3.38%	log(value) ~ year; HAC(2); n=19; R^2=0.768
Trade: B	0.12649	0.01731	[0.09257, 0.16040]	<0.001	+13.48%	log(value) ~ year; HAC(2); n=19; R^2=0.845
Trade: U	0.09322	0.01797	[0.05800, 0.12844]	<0.001	+9.77%	log(value) ~ year; HAC(2); n=19; R^2=0.735

Series / predictor	B	SE (HAC)	95% CI for B	p	Annual trend	Model / diagnostic note
Price: N	0.09548	0.01359	[0.06885, 0.12210]	<0.001	+10.02%	log(value) ~ year; HAC(2); n=17; R^2=0.848
Price: R	0.00675	0.00718	[-0.00732, 0.02082]	0.347	+0.68%	log(value) ~ year; HAC(2); n=17; R^2=0.079

Note: Estimates were independently cross-checked using the harmonized historical observations. Specification: ln(observed value) regressed on year with HAC(2) standard errors. B and its confidence interval are in log units per year; annual trend = 100 × [exp(B) − 1]. These are univariate historical trends, not multivariable causal regressions involving rainfall, heat or irrigation. Results of unverified multivariable specifications are excluded.

Table A.3. Nonparametric annual trends (Kendall tau and Theil-Sen slope).

Series	Kendall tau	p	Sen slope / year	95% CI (slope)	Endpoint CAGR	Interpretive direction
Wheat yield (t/ha)	0.712	<0.001	0.03057	[0.01747, 0.04186]	1.10%	Increasing
Rice yield (t/ha)	0.765	<0.001	0.0248	[0.01694, 0.03266]	1.49%	Increasing
Maize yield (t/ha)	0.935	<0.001	0.1704	[0.151, 0.1999]	4.02%	Increasing
Sugarcan yield (t/ha)	0.830	<0.001	1.217	[0.9542, 1.499]	1.98%	Increasing
Potato yield (t/ha)	0.577	<0.001	0.3838	[0.2158, 0.5281]	1.49%	Increasing
Banana yield (t/ha)	0.890	<0.001	0.4406	[0.3667, 0.5485]	8.08%	Increasing
Edible-oil imports (000 t)	0.743	<0.001	91.3	[71.3, 107.8]	3.48%	Increasing
Edible-oil bill (PKR bn)	0.883	<0.001	24.37	[15.43, 39.45]	17.71%	Increasing
Wheat price, nominal (PKR/unit)	0.868	<0.001	109.4	[67.53, 189]	13.82%	Increasing
Wheat price, real (source units)	0.074	0.715	17.25	[-53.29, 76.28]	2.41%	Uncertain

Note: Theil-Sen slopes use observed annual units and 95% confidence intervals; Kendall tau and two-sided p-values provide nonparametric trend measures. Endpoint CAGR is descriptive and need not match fitted HAC log-linear trends. Missing years are not interpolated. The edible-oil import bill is expressed in PKR billions for descriptive comparability. Quantities, monetary values and wheat prices retain different physical/economic units and must not be compared as magnitudes. Source: Author calculations from the historical crop, trade and price observations described in Chapter 4.

Appendix B: Data-Source Summary and Legal/Reuse Notes

The project source register remains the authoritative audit document. The summary below lists the principal source families expected in the thesis. Dataset-specific licenses and third-party restrictions must be checked at download time.

Table B.1. Principal data-source families and provenance/reuse rules.

Source family	Role	Reuse/provenance rule
FAO / FAOSTAT / AQUASTAT / WaPOR	Agriculture, water, prices, trade, food loss, remote-sensing water productivity	Many FAO statistical products are openly reusable with attribution; verify dataset-specific terms and third-party content.
World Bank WDI / CCKP	Macroeconomics, population, merchandise trade, fuel shares, debt, reserves, current account and climate context	World Bank-produced open data generally support reuse with attribution; verify third-party indicators.
WRI Aqueduct	Water-stress indicators and spatial layers	Open dataset; cite version and acknowledge prioritization/screening limitations.
Government of Pakistan / MNFSR / PBS / Finance	National agriculture, trade, census, economic survey	Official public information; cite exact publication/table and preserve definitions.
ADB	Pakistan value-chain and post-harvest studies	Many ADB-owned publications are Creative Commons; verify the specific publication license.
Scientific literature / AGRIS records	Preservation, coatings, shelf life, treatment effects	Copyright varies; extract data within lawful scholarly use and cite the original article, not only AGRIS when possible.
PMD or other restricted station data	Meteorological observations	Do not redistribute or assume open reuse if terms/fees restrict it; use open climate datasets where reproducibility is required.
UN Population Division / UN WPP; UNFPA	Population, fertility, age structure and demographic-transition context	Cite edition/year and preserve whether figures are estimates, projections or rounded publication displays.
UN Comtrade / World Bank WITS	Exact-HS crude oil, petroleum products, LNG and gaseous natural-gas trade	Retain reporter year, trade flow and component coverage; do not treat absent components as zero.
Our World in Data / Energy Institute / EIA-derived energy series	Oil/gas production and consumption, fossil-fuel context and physical energy dependence	Retain source unit and year; display converts oil/gas to MMbbl/d and MMscf/d while retaining TWh for traceability.

Appendix C: Supplementary analytical evidence and figure provenance

This appendix summarizes the analytical provenance supporting the principal findings. Detailed regression diagnostics, farm-screening inputs and investment-case sensitivity reports are retained as optional technical supplements. The manuscript remains independently interpretable; readers requiring exact model specifications and input schedules may consult the accompanying technical annex.

C.1 Econometrics: Fourteen Model-Level Analyses

The analyses cover six crop-yield series; edible-oil import quantity, bill and unit value (T_Q, T_B, T_U); nominal and real wheat wholesale prices (P_N, P_R); and three macroeconomic series (M_G, M_P, M_PC). Model documentation includes coefficient estimates, goodness of fit, residual diagnostics and influence tests.

C.2 Farm Economics: Six Commodities

Representative assessments cover banana, maize, potato, rice, sugarcane and wheat. Supporting evidence includes retained output, farm operating margins, revenue and cost comparisons, break-even yields and uncertainty associated with local input assumptions.

C.3 Preservation and Irrigation Economics: AG01, AG02 and AG03

The investment cases assess AG01 wheat storage, AG02 rice drying and AG03 canal/water recovery. Appraisal evidence includes point-forward and labeled full-life calculations; identical timelines or starting cash flows do not provide independent historical project validation; discounted cash flows; and sensitivity testing against material cost, performance and valuation assumptions. The AG03 results reflect the revised analysis completed in October 2026.

C.4 Choropleth Coverage and Spatial Guardrails

The two new 2025 choropleths use only seven countries with traceable values in the synthesis. Global/all-selected-country maps for water stress, water productivity, food imports or yield require audited country-specific underlying rows, units and year selection, and have not been fabricated.

Data Availability and Reproducibility

This synthesis integrates publicly available national and international statistics, published scientific evidence, derived indicators, GIS layers and transparent scenario assumptions for Pakistan and selected international comparators. Primary observations are distinguished from harmonized analytical series, and the reference year, geography, unit, source family and evidence limitations are documented wherever available. The national macro-climate analysis spans 2000-2025 where coverage permits; the main historical crop panel spans 2007-2024. International comparisons use the latest compatible observations, which do not necessarily describe a common year. Technical reproducibility records are retained separately without requiring readers to consult internal working-file names.

Declarations

Funding: The working manuscript declares that this research was undertaken independently and did not receive an external research grant or commissioned funding. The author is responsible for confirming the funding statement immediately before submission.

Conflict of interest: The author founded enerbrill and develops Brill-Viz, a platform used in this research. Brill-Viz and related software may have commercial value; this is disclosed as a potential commercial interest. The author is responsible for confirming any additional relevant relationships at submission.

Authors' contributions: The Authors, Khan Arshad and Uzma Khan Marwat, conceived and designed the water-agriculture and food synthesis, selected and critically reviewed the literature and primary datasets, developed the research questions and comparison framework, integrated national and international data, designed and interpreted statistical and economic analyses, coordinated the GIS and visualization programme, and prepared the manuscript. The authors are responsible for source verification, quantitative interpretation and approval of the final submitted version.

Use of analytical tools: Brill-Viz and associated Research, Economics, Generic Panels and Flowcharts workflows support data preparation, analytical calculations, statistical visualization, figure design and reporting. Model specifications, numeric results, spatial accuracy and final interpretation remain the authors' responsibility.

About the Authors



Khan Arshad is a petroleum geologist, exploration professional, independent researcher and developer of scientific data-analytics and visualization tools, with nearly three decades of professional experience in oil and gas exploration, regional geological studies, petroleum-system analysis, prospect evaluation, petroleum economics and exploration-project management. He holds an M.Sc. in Petroleum Geology from the University of Aberdeen, United Kingdom, and an M.Sc. in Geology from the University of Karachi, Pakistan.

His professional career has included technical and managerial assignments in Pakistan with Baker Hughes INTEQ, OMV, PETRONAS, MND, Eni and Dewan Petroleum. His experience encompasses wellsite and operations geology, seismic and petrophysical interpretation, sequence stratigraphy, regional basin analysis, new ventures, prospect generation, exploration-risk and reserves assessment, exploration-team leadership and major exploration-project management.

A substantial part of his career has involved multidisciplinary integration of geological, geophysical, petrophysical, geochemical and economic evidence. His regional work has covered major sedimentary basins and tectonic provinces of Pakistan, including the Middle and Lower Indus basins, Kirthar and Sulaiman fold belts, Potwar Basin and Punjab Platform. This background has contributed to a broader interest in how complex natural-resource systems can be evaluated through integrated data, quantitative analysis and transparent visualization.

He is currently the founder of **enerbrill**, where he combines geoscience, energy-sector experience, data analytics, scientific visualization and software development. He has independently developed **Brill-Viz**, an integrated analytical and visualization platform, together with specialized applications for probabilistic volumetrics, geological chance-of-success assessment, petrophysical evaluation, Total Organic Carbon estimation, decision analysis, mind mapping, research synthesis and AI-assisted document intelligence.

His recent research has broadened from petroleum and energy systems into interconnected questions of water security, agricultural productivity, food security, climate, demography, trade, energy dependence, infrastructure, economic resilience and sustainable resource management. His particular interest lies in combining heterogeneous datasets from multiple disciplines into transparent analytical frameworks that distinguish observed evidence, derived indicators, uncertainty and interpretation.

As leading author of this synthesis, Khan Arshad has coordinated the overall research conception and development of the study, working collaboratively with the co-author across data integration, analytical design, comparative-country assessment, interpretation and visualization. His principal contributions include the multidisciplinary analytical framework, statistical and economic analysis, research synthesis, visualization architecture and integration of the relationships among Pakistan's water resources, agriculture, food production, trade, post-harvest systems, demography, energy exposure and long-term economic resilience.



Uzma Khan Marwat is a GIS and data-analytics professional specializing in Geographic Information Systems (GIS), spatial analysis, business intelligence, data visualization and digital solutions. She holds an MBA in Finance and a BBA, combining geospatial and analytical expertise with an understanding of business, financial and development-sector decision-making.

Her professional experience includes development-sector and infrastructure-related work in Pakistan, particularly in water, sanitation and hygiene (WASH), housing rehabilitation, spatial data management and digitalization. She has contributed to GIS-based mapping, spatial analysis, monitoring dashboards and digital workflows designed to transform complex spatial and non-spatial datasets into practical information for planning, monitoring and decision support.

Her technical experience includes ArcGIS Pro, Power BI, geospatial data visualization, spatial database management and analytical tools for project monitoring and management. Her broader professional interests lie at the intersection of geography, data, economics and sustainable development, with particular emphasis on using spatial intelligence to understand geographical disparities, infrastructure constraints and development challenges.

As co-author of this synthesis, Uzma Khan Marwat has collaborated in the development and integration of the research, with particular contributions to the spatial, socioeconomic and development dimensions of the study. Her GIS and data-analytics background supports the analysis of water availability, irrigation, agricultural productivity, WASH access, regional inequality and the integration of environmental, socioeconomic and geospatial information. She has also contributed to the broader interpretation and presentation of evidence, helping connect national and international quantitative analysis with the geographical and development contexts in which water, food, infrastructure and resource-security challenges occur across Pakistan.

About This Collaborative Research

This synthesis brings together the authors' complementary backgrounds in natural-resource evaluation, geospatial analysis, quantitative research, economics, data analytics, visualization and sustainable-development assessment. It approaches Pakistan's water-agriculture-food system as an interconnected resource, production and socioeconomic system involving water availability and efficiency, agricultural productivity, climate and groundwater, food preservation and storage, trade, demography, energy exposure, infrastructure, economic capacity, WASH conditions and spatial inequality.

The research has been developed through close collaboration, consultation and coordination between both authors, with their respective technical backgrounds contributing complementary perspectives throughout the study. Research questions, datasets, analytical approaches, comparative frameworks, interpretations, figures and synthesis conclusions have been progressively reviewed and integrated as part of this collaborative process.

Analytics, Visualizations, Statistics and Economics are done with Brill-Viz, while Geo-Spatial analysis are done with specialist GIS software.

Glossary and Definitions

Definitions used in the synthesis. Where an indicator has several accepted conventions, the denominator, valuation basis, accounting boundary and observation period used in this study govern its interpretation.

Accounting boundary. The defined system, geography, sectors and stages included in a resource or economic calculation.

Adjusted R^2. Coefficient of determination adjusted for the number of model predictors and observations.

Agricultural value added. Agriculture-sector output less intermediate inputs under the stated national-accounts definition.

Annualized cost. A capital or total cost expressed as an equivalent amount per year using stated life and discount assumptions.

Aquifer. Geological unit capable of storing and transmitting groundwater.

ARDL. Autoregressive distributed lag model relating an outcome to its own lags and current/lagged predictors.

Area-weighted mean. An average in which each geographic unit contributes in proportion to its area.

Autocorrelation. Statistical dependence between observations or model errors separated in time or space.

BACI. CEPII harmonized bilateral international trade database, derived from customs records.

Balance of payments. Statistical record of transactions between residents and non-residents.

Barrage. River control structure that regulates and diverts flows, especially into irrigation canals.

Baseline scenario. The reference set of assumptions against which alternative outcomes are compared.

Benefit-cost ratio (BCR). The ratio of discounted project benefits to discounted project costs under a specified appraisal boundary.

Blue water. Surface water and groundwater available for human and ecosystem use.

Break-even point. The level of output, price, cost or utilization at which a specified financial criterion is exactly met.

CAGR. Compound annual growth rate over a specified period.

Canal command area. Land intended or equipped to receive irrigation from a specified canal network.

Capital expenditure (CAPEX). Upfront or subsequent expenditure on long-lived assets such as irrigation works, machinery or storage facilities.

Cash flow. Money received or paid during a specified period; investment appraisal ordinarily considers incremental flows.

CHIRPS. Climate Hazards Group InfraRed Precipitation with Station data; a gridded precipitation dataset.

Climate anomaly. Departure of observed climatic conditions from a stated reference climatology.

Cointegration. Stable long-run relationship among certain non-stationary series.

Cold chain. Temperature-controlled handling, storage and transport maintained through successive stages of a value chain.

Confidence interval. Interval estimated by a statistical method to have a stated long-run coverage probability.

Constant dollars. Monetary values adjusted to a stated reference-year price level.

Consumer price index (CPI). A price index tracking the cost of a defined basket of consumer goods and services.

Consumptive water use. Water consumed through evapotranspiration or otherwise unavailable for immediate reuse within the defined system.

Cost-benefit analysis (CBA). A systematic comparison of an intervention's incremental benefits and costs using an explicit accounting framework.

Crop coefficient (Kc). A factor relating crop evapotranspiration to reference evapotranspiration under specified crop and growth conditions.

Crop water productivity. Crop output or economic value per defined unit of water use.

Crop yield. Harvested production per unit of harvested area, typically tonnes per hectare.

CRS. Coordinate reference system used to locate features geographically.

Current account. Balance of trade in goods/services plus primary and secondary income.

Debt-to-GDP ratio. A defined measure of debt stock relative to annual gross domestic product; coverage must be stated.

Deflator. A price index used to convert nominal monetary values into constant-price values.

Dependency ratio. Specified dependent-age population divided by the defined working-age population.

Difference-in-differences (DiD). An estimation approach comparing changes over time between treated and suitable comparison groups.

Discount rate. The rate used to convert future costs or benefits into present values; the basis and perspective must be specified.

Distributary. Secondary irrigation channel carrying water from a larger canal into a service area.

Drought anomaly. A departure from a chosen normal or reference climate condition using a stated metric and period.

Econometrics. Statistical estimation and testing of economic relationships.

Economic elasticity. Percentage change in an outcome associated with a one-percent change in a predictor, under a stated model.

Economic internal rate of return (EIRR). The discount rate that sets net present economic value to zero, using the economic rather than solely financial accounting perspective.

Economic water productivity. Economic value, defined as specified output or value added, divided by a specified volume of water used or withdrawn.

Elasticity of demand. Percentage response of quantity demanded to a one-percent change in a specified price or other variable, under stated conditions.

Embedded water. Water attributed to production through a specified resource-accounting boundary.

Environmental flow requirement. Water retained within a river or aquatic system to sustain defined ecological functions.

Evapotranspiration. Combined evaporation from surfaces and transpiration from plants.

Exchange-rate pass-through. The extent to which an exchange-rate change is transmitted into domestic import, producer or consumer prices.

External renewable water resources. Renewable freshwater originating outside a country and entering it through transboundary flows, under a defined accounting convention.

FAO GAEZ. FAO/IIASA Global Agro-Ecological Zones, a framework for assessing agro-climatic conditions and potential suitability.

Farm-gate price. The price received for agricultural output at the farm before downstream transport, distribution or retail margins.

FDR. False discovery rate, the expected proportion of rejected null hypotheses that are false discoveries.

Financial internal rate of return (FIRR). The discount rate at which a project's specified financial net present value equals zero.

Fiscal year. A twelve-month accounting period that may differ from the calendar year.

Fixed effects. Model components that absorb unobserved time-invariant differences across defined entities.

Food availability. Physical supply of food from production, stocks, trade and transfers.

Food import bill. The monetary value of defined food commodities imported over a stated period and valuation basis.

Food loss index. A statistical indicator of losses across specified food-supply stages, excluding or including stages according to its definition.

Food security. Reliable physical, social and economic access to sufficient, safe and nutritious food.

Food self-sufficiency ratio. Domestic production relative to domestic supply for a specified product, period and accounting convention.

Food utilization. Ability to use consumed food through appropriate nutrition, food safety, health and sanitation.

Freshwater withdrawal. Water abstracted from surface-water or groundwater sources for use; it includes water subsequently returned to the system.

GDP (gross domestic product). The total value added generated by resident producers within an economy, plus product taxes less subsidies not included in value added.

GDP deflator. Price index for the goods and services included in gross domestic product.

GDP per capita. GDP divided by population; an average output indicator, not a direct measure of individual income distribution.

GeoJSON. JSON-based exchange format for geographic features and their coordinates.

Gini coefficient. Index of inequality for a specified distribution.

GMIA. Global Map of Irrigation Areas; a spatial product for the mapped extent of irrigation under its stated vintage and definitions.

GMIE-100. Global Map of Irrigated Areas at approximately 100-metre spatial resolution; use the product's stated version and reference period.

Granger causality. A predictive time-series relationship in which past values of one variable improve forecasts of another; it is not proof of causal mechanism.

Green water. Soil moisture supplied by precipitation and available to vegetation.

Gross fixed capital formation. Acquisition less disposal of produced fixed assets over a defined period, adjusted as specified by national accounts.

Groundwater depletion. Decline in groundwater storage over a defined period and area.

Groundwater recharge. Water added to an aquifer through infiltration or other hydrological pathways over a defined period.

Harvested area. The area from which a crop is harvested; it can differ from physical cultivated land because of multiple cropping.

Heteroskedasticity. Unequal error variance across observations or predictor values.

Household water access. A defined household measure of water-source type, accessibility or service level; improved source is not synonymous with safely managed water.

HS code. Harmonized System commodity classification used in international trade.

Import dependency ratio. The proportion of apparent domestic supply associated with imports under a specified commodity accounting formula.

Indus Basin Irrigation System (IBIS). The network of rivers, dams, barrages, link canals and irrigation channels associated with Pakistan's Indus system.

Inflation. The rate of change in a specified aggregate price index over a defined period.

Internal rate of return (IRR). The discount rate at which the NPV of a specified cash-flow stream equals zero; multiple or absent solutions are possible.

Internal renewable freshwater resources. Renewable freshwater generated by precipitation and associated hydrological processes within a country's borders.

International reserves. Foreign-exchange and other qualifying reserve assets available to the monetary authorities under the stated definition.

Investment appraisal. Evaluation of an investment's expected costs, benefits, cash flows, risks and economic or financial viability.

IQR. Interquartile range, the difference between the 75th and 25th percentiles.

Irrigation efficiency. Defined ratio capturing conveyance, application or beneficial use of irrigation water.

Lag. Prior-period value of a variable included in an analysis.

Land-use intensity. Extent of land use per unit area or time under an explicitly stated denominator.

Mann-Kendall test. Non-parametric test for monotonic temporal trend.

Marginal benefit. The additional benefit associated with one incremental unit of an input, intervention or outcome.

Marginal cost. The additional cost associated with one incremental unit of an input or output.

Multicollinearity. Strong dependence among predictors that makes individual coefficient estimates unstable.

Net food-trade balance. The value of specified food exports minus the value of specified food imports.

Net present value (NPV). Present value of incremental benefits less present value of costs, including initial investment.

Nominal price. A monetary value expressed in contemporaneous prices, without inflation adjustment.

Observation vintage. Actual reference date or period represented by an indicator.

Operating expenditure (OPEX). Recurring expenditure for operation, labor, energy, maintenance and other ongoing activities.

Opportunity cost. The value of the best forgone alternative use of a scarce resource.

Ordinary least squares (OLS). Regression estimation that minimizes the sum of squared residuals under the specified linear model.

Panel data. Repeated observations for the same entities across multiple periods.

Payback period. Time required for cumulative defined project cash flows to recover initial investment; simple and discounted versions differ.

Physical crop-water productivity. Crop yield, biomass or other defined physical output per unit of water consumed, supplied or withdrawn, as specified.

Post-harvest loss. Loss of agricultural quantity or quality after harvest within a specified value-chain boundary.

PPP. Purchasing power parity adjustment accounting for relative national price levels.

Present value (PV). Value today of a future cash flow after applying a stated discount rate and timing convention.

Price elasticity. Percentage change in a quantity associated with a one-percent change in price under a stated model.

Production function. An empirical or theoretical relationship between outputs and specified production inputs.

Proxy. An indirect measure used when the desired quantity is unavailable.

Rainfall variability. Variation in precipitation over time, measured using a defined dispersion or anomaly statistic and reference period.

Real GDP. Gross domestic product measured at constant prices using a stated reference or chained-volume method.

Real price. Nominal price adjusted using a specified price index and base period.

Remote sensing. Measurement of surface characteristics by satellite, aircraft or other remote instruments.

Reservoir. Natural or artificial water-storage body, usually associated with a structure or catchment.

Return flow. Withdrawn water that returns to rivers, aquifers or other receiving waters after use; timing and quality can change.

Robust standard error. Uncertainty estimator adjusted for a stated departure from conventional error assumptions.

Scenario analysis. Conditional calculation under explicit assumptions rather than an observation or causal prediction.

Sen slope. Median pairwise slope used to summarize monotonic change in a time series.

Sensitivity analysis. Systematic variation of assumptions or parameters to assess their influence on calculated outcomes.

Spatial resolution. The size or spacing of the smallest mapped geographic unit or raster cell represented in a dataset.

Stationarity. Statistical property of a process with time-invariant distributional features under the chosen definition.

Statistical significance. Assessment of the compatibility of an observed result with a stated statistical null model; it does not indicate practical importance.

Trade balance. Exports minus imports over a defined period and commodity scope.

Transboundary inflow. Water entering a country from a river basin or aquifer originating outside its borders.

Unit value. Value of a traded or produced commodity divided by its reported physical quantity, subject to quality and composition effects.

Value added. Output value less intermediate consumption under the defined economic accounting boundary.

VIF. Variance inflation factor used to diagnose predictor multicollinearity.

WaPOR. FAO Water Productivity through Open access of remotely sensed derived data portal.

WASH. Water, sanitation and hygiene.

Water consumption. The portion of withdrawn or otherwise used water not immediately returned to the same hydrological system, for example because of evapotranspiration.

Water productivity (whole economy). Defined GDP or economy-wide value added divided by the freshwater withdrawal volume under a consistent accounting convention.

Water stress. Ratio or comparable measure of withdrawal pressure relative to available renewable freshwater.

Water stress (SDG 6.4.2). Freshwater withdrawals relative to available freshwater resources after accounting for environmental flow requirements, under the official methodology.

Water stress (withdrawal-based comparator). Annual freshwater withdrawals expressed as a percentage of internal renewable freshwater resources in the specific comparator chart; this is not the SDG 6.4.2 definition.

Water-use efficiency. Economic output or value added relative to a stated measure of water use; definition varies by sector and indicator.

Weighted average cost of capital (WACC). A financing-weighted cost of equity and debt, adjusted as appropriate for tax treatment and appraisal perspective.

WGS 84. World Geodetic System 1984, a standard terrestrial spatial reference used for geographic coordinates.

WKT. Well-known text representation of spatial points, lines and polygons.

Working-age share. Proportion of people within the study's explicitly defined working-age interval.

Yield gap. Difference between observed yield and a clearly specified attainable or reference yield.

Zonal statistics. Summary calculations for raster values within defined polygonal areas, using explicit resolution and weighting rules.

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