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Diagnosing the Value-Chain Constraints and Opportunities for Smallholder Arabica Coffee in Saudi Arabia

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Abstract

Saudi Arabia's Arabica coffee is produced almost entirely by smallholder farmers. Although the local production meets only a small share of national consumption, the sector has expanded substantially in recent years under national development initiatives and strategic investment. This study diagnoses the smallholder value chain in Jazan, Asir and Al Baha through a cross-sectional survey of 347 farms in 14 governorates (May–November 2023). Mean green-bean yield was 0.37 kg per tree (median 0.25), which is within the global smallholder Arabica range, and the top 6.5% of the farms exceeded 1 kg per tree. Water scarcity was the leading production constraint (84.9% of respondents). This prompted a separate, exploratory irrigation survey of 57 Jazan farms (January 2024), which found true drip irrigation to be about 50% more water-productive than basin or stripped-emitter systems, a finding that would need confirmation through controlled trials. Although membership is self-selected and unmeasured confounding cannot be excluded, farmers who belonged to a producer organisation consistently performed better across the value chain. Their yields were higher (0.40 versus 0.23 kg per tree, $p = 0.003$), and this advantage held after adjustment for farm and farmer characteristics (+78%, 95% CI + 33 to +137). In addition, 24% of members undertook on-farm roasting against 3.9% of non-members. These findings point to wider producer-organisation coverage, more efficient irrigation and improved post-harvest handling as priority areas for intervention and future evaluation.

Keywords: *Coffea arabica*; specialty coffee; producer organisations; value-chain upgrading; smallholder market participation; drip irrigation; post-harvest handling



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1. Introduction

Arabica coffee (*Coffea arabica* L.) has been cultivated in the south-western mountains of the Arabian Peninsula since the late fifteenth century [1]. The Saudi escarpment retains a distinctive Arabica landrace called Khawlani whose coffee bean knowledge and associated practices were inscribed by UNESCO on the Representative List of the Intangible Cultural Heritage of Humanity in 2022 [2]. Local production is currently estimated at around 1400 tonnes of clean coffee, up from a much lower baseline before the government rolled

out the FAO-supported Sustainable Rural Agricultural Development (SRAD) Programme. The increase reflects both the agronomic, post-harvest and institutional interventions delivered under SRAD and the concurrent expansion of the smallholder coffee-farmer base. Production is supplied by approximately 4400 smallholder households across Jazan, Asir, Al Baha and Najran. National consumption is estimated at about 78,000 tonnes per year [3]. Saudi Vision 2030 has identified coffee as a heritage crop with cultural and commercial potential. The Ministry of Environment, Water and Agriculture (MEWA) has committed substantial resources to revitalising the sector [4] and has set a national target of 7000 tonnes of green coffee by 2030 [5].

The sector faces a set of structural constraints, each pointing to a clear area for strengthening. Saudi coffee-growing zones lie within the Arabica altitudinal optimum, but temperatures, rainfall and soils are otherwise marginal for the species [6,7]. Biotic pressure is intensifying as warming favours heat-loving pests. The coffee mealybug (*Planococcus* spp.) is among the prominent pests in Saudi coffee farms. Coffee leaf rust (*Hemileia vastatrix*) has recently been confirmed on Saudi Arabica [8], adding to the long-established pressure from *Fusarium* spp. [9]. Labour is widely cited as a constraint, with concerns that an ageing smallholder cohort and limited youth replacement may render physically demanding tasks such as terrace maintenance, on-farm hulling and roasting increasingly difficult to fill. The institutional layer should also be enhanced. The ongoing national initiatives in coffee genetic resource conservation and sector development provide a foundation on which further coordinated breeding could accelerate the development of improved Saudi coffee cultivars. Adoption of recommended best practices is reportedly low [10]. At present, most farmers market their coffee individually; consolidating these sales through cooperatives and agri-marketing service centres offers clear scope to strengthen market access [11]. Finally, expanding collaboration among the existing national research and development institutions would advance integrated coffee research and innovation across the value chain.

Despite these constraints, several structural opportunities reinforce the case for sectoral investment. The Khawlani landrace and related Saudi Arabica selections have co-evolved with the harsh climate of the south-western escarpment over centuries. They carry adaptive traits that are not present in coffee from cooler origins [3]. Domestic demand is rising, with coffee consumption among Saudi youth expanding alongside the growth of specialty cafés and a third-wave coffee culture in the major cities. On the supply side, smallholder land-use patterns suggest room for area expansion without displacing other crops. Institutional support has scaled in recent years. The Saudi Reef and FAO, under MEWA's SRAD programme, operate research, extension and cooperative-development initiatives targeting the four regions. Government subsidies, infrastructure investment and producer-organisation support are already in place [4,5]. Agroforestry offers a complementary intensification pathway: integrating shade trees and companion species would moderate canopy temperature, reduce evapotranspiration losses [12], and improve both terrace microclimate and landscape-scale macroclimate. The lower-altitude wadi and foothill zones below the current Arabica band could host *Coffea canephora* (Robusta) [13], opening a second market segment without competing for Arabica land. Together, these conditions suggest scope for the sector to expand.

Realising the commercial potential of the sector requires more than descriptive accounts. It requires diagnostic understanding of where productivity and value are lost along the chain. Recent peer-reviewed studies have begun to fill this gap. Kathurima et al. [14] showed that Saudi coffee can meet specialty thresholds when handled appropriately. Khemira et al. [15] reported yield-and-quality gains from fertilisation on Saudi mountain terraces. Mehrez et al. [11] documented marketing strategies in Jazan and flagged collective action as the strategic frontier. Sadiddin et al. [16] analysed the economic viability

and structural constraints facing the Saudi highland coffee sector, mapping a path toward sectoral sustainability. What is still missing is an integrated account covering demographic analysis, tree population, irrigation, pest management, post-harvest handling, sale form and price dynamics.

These constraints are not unique to Saudi Arabia, and the international literature on smallholder coffee offers both comparators and cautions. Producer organisations are widely reported to raise smallholder performance. Cooperative membership has been associated with higher prices and incomes in Ethiopia [17] and with improved commercialisation in Rwanda [18], while social capital built through partnership arrangements has been shown to shape smallholder positions within coffee global value chains [19]. The identification problem that accompanies such findings is also well documented: because membership is chosen rather than assigned, better-resourced farmers select into it [17,18]. Socioeconomic characteristics and technology adoption similarly condition smallholder coffee productivity elsewhere [20]. On the production side, comparative work on irrigated and rainfed Arabica shows that agronomic response depends on how water is delivered rather than on volume alone [21]. In addition, precision-farming approaches have been proposed specifically for mitigating the biotic and abiotic stresses facing coffee in Saudi Arabia under climate change [22]. What is not established is whether these patterns hold in an emerging, water-scarce, high-income origin where coffee is a heritage crop rather than a livelihood staple, and where almost no farm-level evidence has been published.

This study therefore asks a single diagnostic question: where along the smallholder coffee value chain in Saudi Arabia are productivity and value lost, and which constraints are amenable to intervention? Following the value-chain approach of Kaplinsky and Morris [23], we treat the chain as three sequential nodes—on-farm production, post-harvest handling and marketing. At each node, we further assess what is produced, what is captured, and what institutional arrangements govern the transfer between nodes. The paper is intended as a systematic farm-level diagnostic and an exploratory value-chain assessment rather than a theoretical contribution to value-chain scholarship. On that basis, its contribution is threefold: the first systematic farm-level characterisation of this origin; identification of producer-organisation membership as the one institutional factor that operates across all three nodes, tested against the selection explanation rather than asserted; and an explicit separation of what the evidence establishes from what it merely suggests. The economic analysis of cost structure and farm viability from the same survey is reported in a companion paper [16]; the present paper diagnoses the agronomic and value-chain constraints.

2. Materials and Methods

2.1. Study Area

The study was conducted in the three traditional coffee-producing regions of south-western Saudi Arabia: Jazan, Asir and Al Baha. The producing area lies along the Sarawat escarpment at elevations of about 1000 to 2400 m above sea level, with cultivation in the adjoining wadi systems descending as low as 800 m based on field observations. Mean growing-season temperatures often exceed the 18–22 °C optimum reported for Arabica [6] and mean annual rainfall ranges from 200 to 500 mm per year, well below the 1500 to 2000 mm typical of East African origins [7]. The Sarawat terrace soils are shallow, rocky and poorly buffered against dry-season stress [3,15]. Coffee is grown on small, terraced plots, with the Khawlani landrace dominating Jazan and a mix of related landraces, natural hybrids and other introductions cultivated in Asir and Al Baha [3]. The 14 governorates sampled in this study cover the principal production catchments across the three regions (Figure 1).



Figure 1. Coffee-producing governorates within the three traditional coffee-growing regions of south-western Saudi Arabia (Jazan, Asir and Al Baha). Shaded governorates indicate areas with active smallholder coffee cultivation. Source: Ministry of Environment, Water and Agriculture, Food and Agricultural Organization of the United Nations FAO (Geospatial Unit Department).

2.2. Study Design and Sampling

A cross-sectional household survey was conducted between 2 May and 4 November 2023, with 99.7% of interviews completed by the end of October 2023. A separate irrigation survey was subsequently conducted in Jazan between 5 and 8 January 2024 to address the irrigation data gap identified in the main survey. Both instruments were semi-structured questionnaires administered in Arabic by FAO experts through face-to-face or telephone interviews, after pre-testing with ten farmers in Jazan.

The main-survey sample size was determined using Cochran's formula [24] for a target population of 3000 coffee-farming households. This was the best estimate available from published sources [3] when the survey was designed in early 2023. A more recent estimate from the Saudi Reef Programme places the current producer base at approximately 4400 households across Jazan, Asir, Al Baha and Najran. Najran was excluded because it is an emerging coffee-producing area that was not yet established at the time of the survey and currently contributes under 1% of national production. At 95% confidence and

$p = 0.5$, Cochran's formula with finite-population correction requires 341 respondents for a population of 3000 and 354 for a population of 4400. Our survey achieved a sample of 347 which delivers a margin of error of 4.95% under the former and 5.05% under the latter, so the reported proportions carry approximately the stated $\pm 5\%$ precision on either assumption. A multi-stage design selected the three regions purposively and allocated respondents by probability proportional to size, yielding 255 in Jazan, 66 in Asir and 26 in Al Baha (Table 1), drawn at random from various lists of coffee-farming households provided by MEWA regional offices. The sample was therefore representative of the three main producing regions, which together account for roughly 99% of national production. Refusals during fieldwork were few and each was replaced, so non-response is not expected to bias the estimates.

Table 1. A sampling frame for the main survey with estimated coffee-farming households (2023) and respondents sampled, by region and governorate.

Region	Governorate	Estimated Farmers, n (%) *	Respondents, n
Jazan	Al Dayer	785 (35.7)	91
	Fayfa	449 (20.4)	52
	Al Aridah	311 (14.1)	36
	Al Edabi	242 (11.0)	28
	Al Reeth	216 (9.8)	25
	Harub	198 (9.0)	23
	Jazan subtotal	2200 (73.3)	255
Asir	Rijal Al'ma	264 (43.8)	29
	Al Majaridah	109 (18.2)	12
	Abha	91 (15.2)	10
	Sarat Abidah	82 (13.7)	9
	Muhayil	55 (9.2)	6
	Asir subtotal	600 (20.0)	66
Al Baha	Al Makhwah	108 (54.0)	14
	Qilwa	77 (38.5)	10
	Al Mandaq	15 (7.5)	2
	Al Baha subtotal	200 (6.7)	26
Total		3000 (100)	347

* Governorate percentages are shares within each region; regional percentages (in subtotal rows) are shares of the national total. Respondents were allocated by probability proportional to size and drawn at random from the frame.

The irrigation survey was an independent follow-up exercise rather than a sub-sample of the main survey. Its 57 respondents were sampled separately and purposively from coffee-farming households in four Jazan governorates: Al Dayer ($n = 25$), Faifa ($n = 19$), Al Edabi ($n = 7$) and Al Aridah ($n = 6$), which together account for about 81% of Jazan's coffee farmers (1787 of 2200; Table 1). Because these four governorates were selected to capture the observed range of irrigation practice in Jazan rather than by probability sampling of the producer population, the irrigation findings are treated throughout as exploratory. They are not extrapolated to the main-survey sample, to the remaining Jazan governorates, or to Asir and Al Baha.

2.3. Variables and Derivations

The main instrument captured six blocks of variables: (i) demographic characteristics; (ii) farm structure (size, tree population, expansion potential); (iii) production performance, given as 2022/23 season green-bean output; (iv) production constraints, including the most-limiting challenge, pest and disease pressure, seedling source and extension access; (v) post-harvest handling and value addition (drying, storage, on-farm processing); and (vi) institutional factors including marketing dynamics and producer-organisation membership. The irrigation survey added irrigation system, drip type if any, reasons for non-adoption, water source, water quantity, water cost, perceived water availability and quality, and total production cost. Two analytic variables were derived from the main survey. Tree density (trees ha⁻¹) was calculated as (Total Coffee Trees × 10,000) ÷ Coffee-farm area in m². The ratio of productive trees was calculated as a percentage of the total trees per farm. Yield was reported as green-bean equivalent in kg per productive tree, with farmer-reported dry cherry converted at a 2:1 ratio (50% out-turn) [4,6]. For the irrigation survey, three derived variables were used: water applied per tree per season (m³), irrigation cost per tree (SAR), and water productivity (kg of green beans per m³).

2.4. Data Handling and Statistical Analysis

Responses were cleaned in Microsoft Excel Version 16.111.1 (26071913). Statistical analysis was carried out in Python 3.10.12 using pandas 2.3.3 for data management and NumPy 2.2.6 for numerical computation. The Kruskal–Wallis H, Mann–Whitney U, Pearson’s chi-square, Fisher’s exact test, Pearson and Spearman correlations, the ordinary least-squares and logistic regressions, the propensity-score weighting and the bootstrap confidence intervals were computed from implementations written directly against NumPy, together with the normal, chi-square and Student t distribution functions required for the corresponding *p*-values. Each implementation was validated against published reference values and independently cross-checked by permutation and by exact enumeration before use. Free-text spelling variants were harmonised before tabulation. The four farms reporting tree densities above 10,000 ha⁻¹ were retained for descriptive reporting but Winsorised at the 95th percentile (about 6700 ha⁻¹) for inferential analyses involving density. In the irrigation survey, the Faifa governorate results were flagged because some respondents reported diverting irrigation water to other (non-coffee) crops alongside their coffee. Multiple-response items (challenges, pests, channels, forms sold) were treated as binary indicators per category, so proportions can sum to more than 100%.

Continuous variables were summarised as medians with interquartile ranges because the distributions of yield, tree count and the irrigation variables were markedly right-skewed (Fisher–Pearson skewness: per-tree yield 2.43, water applied per tree 3.29, production cost per tree 3.25). Differences across categorical predictors with three or more groups were tested using the Kruskal–Wallis H test, two-group comparisons using the Mann–Whitney U test, and associations between categorical variables using Pearson’s chi-square, with Fisher’s exact test where expected counts fell below five. For every test we report the test statistic, the degrees of freedom where applicable, the exact sample size contributing to the comparison, the *p*-value and an effect size: epsilon-squared for Kruskal–Wallis, the rank-biserial correlation for Mann–Whitney and Cramer’s V for chi-square. Confidence intervals for differences in medians were obtained by bootstrap resampling with 10,000 replicates. Significance was set at *p* < 0.05. Given the pronounced skew of the irrigation variables, Spearman’s rank correlation is reported as the primary measure of pairwise association in the irrigation survey, with Pearson’s coefficient reported alongside it for comparability with earlier work. Influential observations were assessed

using leverage and Cook's distance, and correlations were re-estimated with influential points excluded as a robustness check.

Full outputs of the membership-selection, adjusted-yield, on-farm-hulling and propensity-score models, together with covariate balance before and after weighting and a by-organisation-type sensitivity analysis, are reported in Supplementary Materials (Sections S1–S8, Tables S1–S6). The models used complete-case (listwise) analysis. All 347 farms reported the model covariates; the 38 farms carrying only young, not-yet-bearing trees had no harvest and therefore no per-tree yield or post-harvest activity and were excluded from the outcome models. The membership-selection model was therefore estimated on all 347 farms, while the adjusted-yield and on-farm-hulling models were estimated on the 309 producing farms. Propensity-score weighting used average-treatment-effect-on-the-treated weights, with common support imposed by trimming propensity scores to the 0.05–0.95 (224 farms) interval; weights were neither stabilised nor truncated, and the estimate was unchanged under 1st/99th-percentile truncation. E-values were computed following the approach of VanderWeele and Ding [25]. A summary of the implementation and its validation is provided in the Supplementary Materials (Section S9, Table S7).

Membership of a producer organisation is self-selected rather than assigned, so differences between members and non-members cannot be attributed to membership based on bivariate comparison alone. Three complementary analyses were therefore added. First, a logistic model of membership on farmer and farm characteristics was estimated to characterise selection explicitly. Second, per-tree yield (natural-log transformed) was regressed on membership and covariates by ordinary least squares (OLS) with heteroskedasticity-consistent (HC1) standard errors, and binary value-chain outcomes were modelled by logistic regression. Third, the membership differential among members was re-estimated by inverse-probability weighting (IPW) on the propensity score (the estimand analogous to the average treatment effect on the treated), with covariate balance assessed through standardised mean differences and common support restricted to propensity scores between 0.05 and 0.95 [26]. The sensitivity of the adjusted estimates to unmeasured confounding was quantified using E-values [25]. Covariates comprised log coffee area, log tree count, years of education, farming experience, age, extension-contact frequency and region. These models adjust for measured confounding only; they do not identify causal effects, and the resulting estimates are interpreted as adjusted associations throughout.

3. Results and Discussion

3.1. Farmer and Farm Profile

3.1.1. Demographic Characteristics

The household heads of the sampled farms were almost entirely male and ageing, with 42.1% over 60 years and only 2.6% aged 18–30 (Table 2; consistent with the demographic profile reported in [16]). The predominance of male respondents and the older age profile both reflect the respondent-selection strategy, which primarily targeted farm owners or household heads rather than all individuals involved in the coffee value chain. Rural women also play important roles in coffee production and post-harvest activities, but their contributions were not specifically captured by the survey design. The age profile also highlights an opportunity for continued engagement of younger generations through the ongoing national initiatives supporting the development of the Saudi coffee sector. Education was bimodal: 21.9% had no formal schooling and 20.7% held a university qualification, meaning a single advisory format will not reach all farmers; oral and demonstration-based extension is needed for the former, while written, mobile-application and short-course channels suit the latter.

Table 2. The demographic characteristics of the sampled coffee-farming households (n = 347). Percentages are rounded to one decimal place and may not sum to exactly 100%.

Variable	Category	n (%)
Region	Jazan	255 (73.5%)
	Asir	66 (19.0%)
	Al Baha	26 (7.5%)
Gender of household head	Male	345 (99.4%)
	Female	2 (0.6%)
Age band	18–30 years	9 (2.6%)
	31–40 years	42 (12.1%)
	41–50 years	73 (21.0%)
	51–60 years	77 (22.2%)
	Over 60 years	146 (42.1%)
Education	No formal schooling	76 (21.9%)
	Primary	74 (21.3%)
	Secondary	33 (9.5%)
	High secondary	81 (23.3%)
	Vocational	11 (3.2%)
	University	72 (20.7%)
Farming experience	Less than 5 years	57 (16.4%)
	5–10 years	73 (21.0%)
	11–15 years	23 (6.6%)
	16–20 years	14 (4.0%)
	Over 20 years	180 (51.9%)

3.1.2. Farm Structure

Total household land area ranged from 150 to 100,000 m², with a median of 5000 m². The area allocated to coffee ranged from 80 to 60,000 m² (median 1200 m²), representing about a third of household land (mean 35.5%, median 32%). Two-thirds of household land therefore remains under other uses or fallow. Land availability is therefore not the binding constraint on coffee-area expansion; the binding factors are biophysical and institutional rather than territorial.

Total coffee-tree populations per farm ranged from 20 to 14,000, with a median of 320 trees (mean 624, bootstrap 95% CI 517 to 751). Productive trees averaged 454 per farm and unproductive trees averaged 171. The mean productive ratio was 70.3% and the median was 84%. Extrapolating the survey mean to a national tree population is uncertain and is best expressed as a range. When applied to the estimated 3000 coffee-farming households at the time of the survey [3], the mean implies about 1.87 million trees (95% CI 1.55 to 2.25 million). This estimate provides an indicative assessment of the current scale of the sector, updates the earlier estimation of about 400,000 trees [3,27], and may complement official statistics in supporting future planning. Because the tree counts were self-reported and not independently verified, this estimate is best read as an indicative order of magnitude rather than a national inventory, and a census of coffee holdings would be required to establish the exact population.

The median tree density was 2500 per hectare (IQR 2437–3000; mean 3129), placing the typical KSA smallholder system at the upper end of conventional Arabica spacing in East African origins [7]; there is therefore little immediate scope for productivity gains from intensification of plant population alone in existing coffee farms. Expansion onto new land is the alternative route, and 83.9% of respondents planned to expand their coffee plantings (16.1% did not). Estimated seedling demand over a three-year planning horizon averaged 850 seedlings per household (median 250; bootstrap 95% CI 645 to 1093), implying a stated national demand of about 2.5 million seedlings (95% CI 1.9 to 3.3 million) across the estimated population of 3000 households. Because these were self-reported planting intentions, the figure is indicative but can guide national coffee seedling-supply planning.

3.2. Node 1: Production Constraints and Opportunities

3.2.1. Production Performance

Of 347 respondents, 309 (89.0%) reported green-bean production for the 2022/23 season, with yield ranging from 0.01 to 4.0 kg of green beans per tree (median 0.25; mean 0.37, SD 0.45). Most respondents (79.6%) produced less than 0.5 kg of green beans per tree, 6.5% reached or exceeded 1 kg, and only eight farms exceeded 2 kg. Regional medians were 0.30 kg of green beans per tree in Al Baha ($n = 18$), 0.25 in Jazan ($n = 242$), and 0.22 in Asir ($n = 49$), although the omnibus regional difference was not significant (Kruskal–Wallis $H = 1.98$, $df = 2$, $p = 0.37$). The survey mean of about 400 g of green coffee per tree sits within the international range of 90–480 g per tree reported for smallholder Arabica [7]. Saudi coffee plots are exceptionally small by international smallholder standards, allowing more intensive per-tree management than the global norm permits. Although the current average productivity remains below the sector's long-term aspirations, the study demonstrates promising potential for productivity improvement. The highest-performing farms achieved yields exceeding 1 kg of green beans per tree under the same environmental conditions, illustrating that substantially higher productivity is attainable. Continued implementation of improved agronomic practices and ongoing national development initiatives is expected to further enhance coffee productivity across the sector. What separates the median farmer from the top performers is examined under production constraints, cooperative membership, and irrigation practice.

3.2.2. Water Scarcity and Irrigation Practice

Water scarcity was the dominant single most-limiting production constraint, cited by 84.9% of respondents, motivating a separate follow-up irrigation survey in Jazan ($n = 57$) that gives the first systematic account of how Saudi smallholders manage this scarce input. Two-thirds of irrigators (66.7%) sourced water by buying from tankers, 21.0% from private boreholes and 12.3% from rainwater harvesting. Three-quarters (75.4%) perceived their water as inadequate and a further 5.3% as scarce; only 19.3% reported sufficient supply, and 47.4% rated their water saline. Irrigation timing was split, with 43.8% irrigating early in the morning, 28.1% during the day, 22.8% late in the evening and 5.3% at night; the 28% irrigating during the heat of the day represents an evaporative-loss exposure that scheduling extension could address at no infrastructure cost [28]. Basin irrigation around the tree was the dominant practice (59.6%), with 21.1% of the full sample using stripped-emitter drip (drip systems from which farmers had removed emitters to increase water flow) and only 19.3% operating true drip. The dominant barrier to drip adoption was capital cost, cited by 72.7% of non-drip users, followed by slow water output (18.2%), unfamiliarity (6.8%) and clogging (2.3%).

Efficiency varied across systems (Table 3). Median water applied per tree per season was 0.85 m³ under basin, 0.74 m³ under true drip and 0.67 m³ under stripped-emitter

drip. Median irrigation cost per tree per season was 14.81 SAR under basin, 11.90 SAR under true drip and 6.79 SAR under stripped-emitter drip. Median green-bean yield per tree was 0.30 kg under true drip against 0.26 kg under both basin and stripped-emitter drip. The counterintuitive finding that true drip used slightly more water than stripped-emitter drip reflects the dominant single-emitter design of true-drip installations observed in the field. This system requires long run-times to wet the entire coffee root zone, during which evaporation and leaching losses accumulate, especially under the prevalent daytime irrigation. Despite this, water productivity (median kg of green beans per m³ of water) was 0.39 under true drip, 0.26 under stripped-emitter drip and 0.25 under basin, making true drip roughly 50% more water-efficient than either alternative. In water-productivity terms, stripped-emitter drip (0.26 kg per m³) performs essentially like basin (0.25) rather than like true drip (0.39): removing emitters lowers water use and cost but forfeits the precision that makes drip efficient, so its apparent economy does not translate into output. Therefore, the apparent cost and water savings of stripped-emitter drip come at the expense of abandoning the precision that defines drip irrigation, without a corresponding yield improvement and with the same risks of root-zone waterlogging and *Fusarium* predisposition as basin practice. The technical solution is to install drip systems properly customised for coffee, either as a ring of four emitters around the root zone or two parallel driplines with two emitters each. Both designs provide adequate root-zone coverage and remove the under-provisioning that drives farmers to remove emitters. An automated controller delivering water at night, matched to coffee evapotranspiration demand, would further reduce evaporative loss and over-supply, achieving uniform root-zone wetting with neither surplus nor deficit.

Table 3. Irrigation practice in Jazan smallholder coffee farms (n = 57).

Variable	Category	n (%) or Median	Notes
Water source	Buying from tankers	38 (66.7%)	Main cost driver
	Bore hole	12 (21.0%)	
	Rainwater harvesting	7 (12.3%)	
Perceived availability	Inadequate	43 (75.4%)	
	Sufficient	11 (19.3%)	
	Scarce	3 (5.3%)	
Water quality	Good	30 (52.6%)	
	Saline	27 (47.4%)	Quality concern
Irrigation system	Basin around tree	34 (59.6%)	0.85 m ³ , 14.81 SAR/tree
	Stripped-emitter drip	12 (21.1%)	0.67 m ³ , 6.79 SAR/tree
	True drip	11 (19.3%)	0.74 m ³ , 11.90 SAR/tree
Irrigation timing	Early morning	25 (43.8%)	
	During the day	16 (28.1%)	High evaporative loss
	Late evening	13 (22.8%)	Recommended
	At night	3 (5.3%)	Recommended

Water Use, Cost and Yield Associations

Within this sample, per-tree yield was not significantly correlated with the volume of water applied per tree (Spearman rho = +0.08, $p = 0.53$; Pearson $r = -0.053$, $p = 0.70$; $n = 57$), irrigation cost per tree (rho = +0.00, $p = 0.98$; $r = -0.077$, $p = 0.57$), or total production cost per tree (rho = +0.04, $p = 0.75$; $r = 0.045$, $p = 0.74$). This suggests that many farmers may be applying more water than the crop requires. Such over-application carries a clear

cost penalty: water applied was positively correlated with both irrigation cost and total production cost. Because these variables are markedly right-skewed (Fisher–Pearson skewness 3.29 for water applied per tree, 3.25 for production cost per tree and 2.43 for per-tree yield), Spearman’s rank correlation is reported here as the primary measure, with Pearson’s coefficient alongside it for comparability: water versus irrigation cost $\rho = +0.36$ ($p = 0.007$; Pearson $r = +0.61$), water versus total production cost $\rho = +0.51$ ($p < 0.001$; Pearson $r = +0.70$), and irrigation cost versus total production cost $r = +0.757$ ($p < 0.001$). The gap between the rank and product-moment coefficients for water versus irrigation cost indicates that the Pearson estimate is inflated by a small number of high-leverage farms, so this association is best described as moderate rather than strong. Diagnostic assessment identified three farms exceeding the conventional Cook’s distance threshold of $4/n$, including one reporting 7.00 m^3 per tree against a sample median of 0.80 (leverage 0.55, Cook’s $D = 1.22$). Excluding these influential observations left the null yield associations unchanged (water versus yield: Pearson $r = -0.037$, $p = 0.79$; Spearman $\rho = +0.15$, $p = 0.28$), confirming that the absence of a yield return to additional water is not an artefact of individual farms. Across the surveyed farms, the efficiency of water delivery therefore emerged as the main lever for improving water productivity.

Sensitivity Check Excluding Faifa

As a sensitivity check addressing the Faifa data-quality concern flagged in Section 2.4, the correlations were re-computed with Faifa farms excluded ($n = 38$). This pattern held and in fact strengthened: water per tree was now significantly negatively correlated with yield (Pearson $r = -0.32$, $p = 0.04$), while remaining significantly correlated with irrigation cost ($r = +0.42$, $p = 0.006$). The central finding does not depend on Faifa inclusion; if anything, excluding Faifa removes possible bias from non-coffee water allocations and reveals an over-irrigation signal, a finding corroborated by field observations. Because these relationships come from a single-season observational survey rather than a controlled irrigation trial, they should be read as within-sample associations reflecting current management, not as evidence of water use inefficiency; the cumulative, season-long crop response to water is best resolved through controlled trials. Given that water is the scarcest production input in Saudi coffee farming, a dedicated irrigation trial to establish the crop’s optimum water requirement should be a research priority.

Variation Across Governorates

At the governorate level, the same pattern holds. In Al Dayer, the median irrigation cost per tree was 6.25 SAR (mean 13.77) and median yield was 0.38 kg of green beans per tree (mean 0.43). In Al Aridah, the median cost was 25.51 SAR (mean 34.87) for a median yield of 0.22 kg (mean 0.26). The Faifa result (median cost 13.33/mean 27.09 SAR; median yield 0.15/mean 0.20 kg) should be interpreted with caution, since the diversion of water to non-coffee crops noted in Section 2.4 would inflate the apparent water input per coffee tree. Even setting Faifa aside, the cross-governorate pattern aligns with the correlation finding: higher cost is not buying higher yield, and management (system choice, scheduling, basin over-application) is the binding factor. Part of the cross-governorate variation may also reflect altitude effect: Al Dayer sits at a higher elevation than Al Aridah, with Faifa intermediate, and the cooler temperatures and lower evapotranspiration at higher elevations both reduce irrigation demand and bring conditions closer to the Arabica optimum. This negative water–yield association is biologically plausible. Excess water at the root zone can impair root respiration and leach nutrients [28] and can also increase tree susceptibility to root and stem pathogens including *Fusarium* spp. [7]. In the relatively

humid Jazan microclimate, actual evapotranspiration demand is also lower than farmers may assume.

3.2.3. Other Production Constraints

After water scarcity, the next-most-cited single most-limiting production constraints were pests and diseases (6.7%), baboon damage (2.9%) and lack of inputs (2.3%). Among the 177 respondents who reported a most-limiting pest, the coffee mealybug (*Planococcus* spp.) accounted for 79.1% followed by the leaf miner (*Leucoptera* spp.) at 16.9% and the stem borer at 2.8%. On the management side, 55.0% of affected farmers used pesticides, 36.1% applied no control measures, and only 5.0% used cultural practices. These findings carry three implications. First, the dominance of warm-climate pests reflects Saudi coffee's position at the warm edge of Arabica's climatic range, which favours mealybug and leaf miner populations. Second, the high pesticide-use share masks a more concerning pattern. Without species-targeted IPM, broad-spectrum applications risk resistance development and the suppression of natural enemies that would otherwise help regulate mealybug populations. Third, the 36% of affected farmers applying no control measures represents an unprotected yield-and-quality loss that targeted IPM training could substantially reduce. Agroforestry offers an integrated response that addresses all three concerns simultaneously: shade trees moderate canopy temperature and reduce the heat stress that favours warm-climate pests; they conserve the biodiversity that sustains natural enemies of the mealybug and leaf miner; and they reduce reliance on broad-spectrum pesticides that drive resistance and natural-enemy suppression [12]. Disease data were too sparse to support inference, with only seven farmers (2.0%) reporting a most-limiting disease. This does not imply low disease pressure; rather, it may indicate that passive surveillance fails to capture disease incidence. The continued expansion of surveillance, early detection, and integrated disease management programmes will further strengthen the resilience of the Saudi coffee sector as production continues to expand.

Seedling supply was dominated by government nurseries, which served 58.8% of respondents. Farmer-owned nurseries accounted for 29.7%. Private nurseries and farmer-to-farmer exchange accounted for 5.8% each. Government nurseries are an appropriate backbone for a young sector. Expanding the availability of certified coffee seedlings through national nursery programmes will further support the conservation of Saudi coffee genetic resources while ensuring the supply of high-quality planting material. Standardised seed-collection and nursery protocols would help preserve the genetic distinctiveness that underpins the Saudi local landraces, including the Khawlani [2]. A structured national breeding programme would further harness the genetic diversity created through informal seed exchange and the use of volunteer or introduced material for deliberate selection and conservation, safeguarding the landraces for the future.

On-farm extension already reaches most growers: 53.3% of respondents had received at least one extension visit to their farm, a notable achievement given the difficulty of reaching dispersed mountain holdings. The main opportunity lies in increasing the regularity of contact, as 26.5% were visited only occasionally and 8.6% on a regular quarterly basis. When asked which source of advice they relied on most, MEWA staff and other farmers were cited at virtually equal frequency (47.8% and 47.6%). NGOs, private companies and social media accounted for the remainder. Peer-to-peer learning carries half the advisory load by default rather than by design. Any extension scale-up will succeed faster if it recruits high-performing farmers as champions rather than treating them only as recipients [10].

3.3. Node 2: Post-Harvest Handling

3.3.1. Drying Practice and Duration

Drying practice was variable: 48.2% of farmers used uncovered concrete floors, 32.7% used elevated beds with provision for rain covers (recommended practice), 12.9% used uncovered elevated surfaces, and 6.1% used concrete floors with a covering provision. The 48% drying directly on uncovered concrete floors face dust and soil contamination as well as rewetting from any out-of-season rainfall, all of which depress green-bean quality and increase the risk of mould [6,12].

Drying duration averaged 15.5 days (median 14, IQR 7–21, range 3–60). Almost half (46.6%) completed drying within 7–14 days and a further 10.7% in under seven days. Both windows are shorter than the 21-day slow-drying window often associated with natural-process Arabica. This compressed schedule likely introduces moisture-gradient defects that may surface downstream as cup-quality losses, a hypothesis that controlled trials should test. As expected, drying surface was not associated with green-bean yield (Kruskal–Wallis $p = 0.91$), nor was drying duration. Most farmers do not process to the green-bean stage at the farm level, so the yield was recorded as dry cherry and converted to green-bean equivalent using a 50% out-turn (approximately 2 kg of dry cherry to 1 kg of green beans) for natural-process Arabica [6,14]. Therefore, the survey could not capture the post-harvest losses that vary by drying method; such effects appear downstream as cup-quality and price differentials at the marketing node rather than at the field level.

3.3.2. Storage and On-Farm Processing

Storage was dominated by single-layer gunny bags (80.9%), followed by single-layer nylon bags (13.9%), mixed gunny-plus-nylon (3.9%) and plastic buckets (1.3%). None of the 347 farms used hermetic storage bags, a gap that represents a quality risk because green beans and dry cherries may absorb or release moisture in equilibrium with the ambient relative humidity. Non-hermetic containers expose the coffee to repeated moisture cycling, which degrades both physical and sensory quality [29].

Beyond drying, on-farm processing was limited: only 23.3% of farms hulled their coffee at the farm level, with the remaining 76.7% either selling dry cherries directly or delivering to a third-party huller. Only 6.3% of the sampled farms practised on-farm roasting. On-farm hulling was more common among higher-yielding farms (median 0.31 kg of green bean per tree versus 0.23 kg; Mann–Whitney $U = 7314$, $z = -2.78$, $p = 0.005$), reflecting that more productive farmers are better placed to invest in on-farm-hulling capacity.

3.3.3. Drying Challenges

About half (51.5%) of the respondents cited poor weather as the most-limiting drying challenge. In Asir and Al Baha, where the harvest peaks between November and January and coincides with the winter season, rainfall is uncommon, but winter fog may deposit moisture on the drying coffee while cold air suppresses evaporation. Jazan rarely experiences winter conditions, but diurnal cooling is felt at higher elevations from evening through to morning. The dominant drying constraint across the region is the high humidity from the Red Sea. Post-harvest fungal mould development and irregular drying (uneven moisture across the batch) were each cited by 15.5% of the respondents. There are opportunities to further improve post-harvest handling practices through farmer training, improved drying technologies, moisture monitoring, and appropriate storage systems that keep bean moisture low and uniform, limiting fungal growth [30] and thereby maintaining the high quality of Saudi coffee. Lack of suitable drying facilities was cited by 9.4% of the respondents and absence of a moisture metre by 4.9%, the latter compounding both

challenges because farmers without a metre cannot reliably confirm when beans have reached storage-safe moisture.

3.4. Node 3: Marketing and Value Capture

3.4.1. Sales Rate and Value-Form Distribution

Just over half of the sampled farms (57.3%) sold some of their coffee while the remaining 42.7% produced exclusively for home consumption or social distribution. The sellers were heavily commercial rather than marginal, with an average of 64.3% (median 70%, IQR 50–90%) of their production being sold. Per-farm production volume was about five times higher among the sellers than the non-sellers (median 80 kg versus 15 kg of green beans), implying that the commercialisation gap is driven more by scale than by motivation. In a society where coffee is woven into hospitality and gifting customs, the small harvest of a low-volume farm is readily absorbed by domestic and ceremonial use before any surplus is available for the market. Among the sellers, however, value capture stops at the lowest-margin form on most farms: dry cherries dominated, sold by 49.6% of all farms, followed by green beans (26.2%), roasted beans (6.1%) and ground coffee (5.8%). Only 15 of the 199 sellers sold across all four forms.

Nominal prices rise significantly across the processing stages (green about 65% above dry-cherry, roasted about 28% above green), but once out-turn losses (about 50% dry cherry to green) and processing weight loss (about 20% on roasting) are netted out, value addition pays off only when paired with access to higher-price retail or specialty segments rather than the wholesale bands. The price dynamics are presented in detail in Sadiddin et al. [16], which reports the economics findings from the same survey.

3.4.2. Marketing Channels, Customers and Constraints

Marketing was predominantly through direct sales, with 76.4% of respondents selling their coffee through buyer-initiated channels. This points to a ready local market for Saudi coffee, in which smallholders can sell their harvest without involving middlemen. Organising and aggregating these buyer-initiated channels offers scope to convert this demand into higher and more stable returns. Festivals and exhibitions were used by 15.6% of respondents and phone-based marketing by 12.4%. Other marketing channels included social media (10.4%), websites (4.0%) and cooperatives or associations (4.0%). The customer base mirrored this pattern, with direct household sales to Saudi citizens accounting for 45.5% while sales to other farmers, friends and relatives accounted for 6.1%. Other sales went to local roasters (3.5%), institutions (1.7%) and only 0.6% were sold through middlemen.

The most-cited marketing challenges were inadequate production quantities (33.6%) and the absence of a structured market (24.6%), followed by low demand (9.9%), poor prices (9.0%) and limited policy framework (7.0%). Together the first two account for 58% of marketing concerns and explain the channel pattern: an individual farm producing only 80 kg of green coffee per season cannot deliver the steady volumes that a roaster or retailer requires, and organised market infrastructure is still developing, so even high-quality coffee can struggle to reach a premium buyer. Direct marketing remained the predominant sales channel among surveyed farmers, indicating opportunities for further strengthening organised market linkages alongside the ongoing development of the Saudi coffee sector. The same direct channel, however, can be reframed as latent specialty infrastructure: an existing farmer-to-consumer relationship, when paired with provenance branding, agritourism circuits and the cultural prestige of Khawlani origin, can deliver a comparable premium without requiring the conventional roaster-supply architecture.

3.5. Cooperative Membership as a Transverse Value-Chain Lever

Producer-organisation membership was the only institutional variable that produced significant differences at all three nodes of the value chain (production, post-harvest and marketing) and is treated here as a transverse axis. Most respondents (84.4%) belonged to neither a cooperative nor an association; 9.2% ($n = 32$) belonged to a cooperative and 6.3% ($n = 22$) to an association. Because post-harvest and marketing activity presupposes a harvest, the comparisons that follow are restricted to the 309 farms in production (22 association, 28 cooperative and 259 non-members). At the production node, median per-tree yield differed across the three groups (Kruskal–Wallis $H = 9.72$, $df = 2$, $p = 0.008$, epsilon-squared = 0.025, $n = 309$): 0.43 kg of green beans per tree among association members ($n = 22$), 0.31 among cooperative members ($n = 28$) and 0.23 among non-members ($n = 259$). Pooling the two member categories, the median difference against non-members was + 0.171 kg per tree (bootstrap 95% CI + 0.022 to +0.227; Mann–Whitney $U = 8189$, $z = -2.96$, $p = 0.003$, rank-biserial $r = 0.27$, $n = 309$). Association members also had more frequent extension contact (chi-square = 24.46, $df = 8$, $p = 0.002$, Cramer's $V = 0.20$, $n = 309$). At the post-harvest node, on-farm hulling was practised by 72.7% of association members (95% CI 51.8 to 86.8), 53.6% of cooperative members (95% CI 35.8 to 70.5) and 19.3% of non-members (95% CI 15.0 to 24.5) (chi-square = 41.83, $df = 2$, $p < 0.001$, Cramer's $V = 0.37$, $n = 309$), and on-farm roasting by 36.4% (95% CI 19.7 to 57.0), 14.3% (95% CI 5.7 to 31.5) and 3.9% (95% CI 2.1 to 7.0) respectively (24.0% for the two member categories combined, 95% CI 14.3 to 37.4). At the marketing node, association members used a mean of 2.14 marketing channels against 0.75 for cooperative members and 0.36 for non-members (Kruskal–Wallis $H = 34.12$, $df = 2$, $p < 0.001$, epsilon-squared = 0.105, $n = 309$). Sales participation was 100% among association members (95% CI 85.1 to 100), 82.1% among cooperative members and 59.5% among non-members; resting on $n = 22$, the 100% should not be read as evidence that every association member sells. Figure 2 ranks the strength of this lever across the six indicators, showing its largest effects at the processing and marketing nodes (9.4-fold for on-farm roasting, 5.9-fold for marketing channels) and more modest gains at the production node.

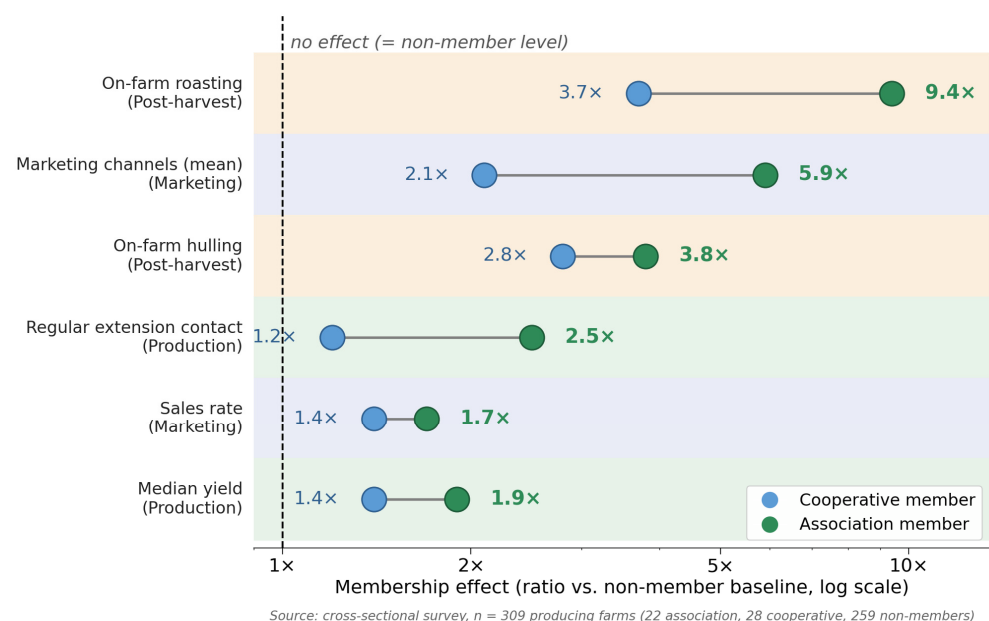


Figure 2. The strength of the producer-organisation lever at each value-chain node, shown as the ratio of each membership group (association, cooperative) to the non-member baseline ($1\times$ = no difference). Underlying proportions and their Wilson 95% confidence intervals are given in Section 3.5; ratios from the small member groups carry wide uncertainty.

Because the member groups are small (22 association and 28 cooperative members against 259 non-members), these proportions carry wide margins of error, reported above as Wilson 95% confidence intervals. The between-group ordering is consistent across all six indicators and the intervals for association members and non-members do not overlap for either processing indicator; the precision of any individual small-group estimate is nevertheless limited, and the ratios plotted in Figure 2 inherit that imprecision. Selection is a further concern: membership is self-selected rather than assigned, so these contrasts cannot by themselves be read as effects of membership. A logistic model of membership on farmer and farm characteristics confirms that selection is present and systematic ($n = 347$, McFadden pseudo- $R^2 = 0.22$). Each additional year of schooling raised the odds of membership by 12% (odds ratio, OR = 1.12, 95% CI 1.03–1.22, $p = 0.007$) and each additional year of farming experience by 5% (OR = 1.05, 95% CI 1.01–1.09, $p = 0.029$). Members also operated substantially larger holdings: standardised mean differences between members and non-members were 0.65 for tree count, 0.58 for coffee area and 0.63 for years of education. Better-resourced, better-educated and more experienced farmers are therefore over-represented among members, exactly as a selection account predicts.

Nevertheless, the differential survives adjustment for those characteristics (Figure 3). In an ordinary least-squares model of log per-tree yield adjusting for farm and farmer characteristics ($n = 309$, $R^2 = 0.13$, HC1 robust standard errors), membership remained associated with a 77.9% (1.78 $\times$) higher per-tree yield (beta = 0.576, 95% CI 0.288–0.863, $p < 0.001$). Inverse-probability weighting on the propensity score, restricted to the 224 farms on common support, gave a smaller but concordant estimate of +67.1% (1.67 $\times$; 95% CI + 11.7% to +144.3%). On-farm hulling showed the same pattern: adjusted for the same covariates, members had 3.67 times the odds of hulling their own coffee (OR = 3.67, 95% CI 1.76–7.65, $p < 0.001$, $n = 309$). Two independent adjustment strategies therefore agree that the membership differential is not simply a restatement of the observable characteristics that predict joining. Estimating the two organisation types separately (Supplementary Table S5) gives the same picture: association members (adjusted+ 103.6% per-tree yield) and cooperative members (+60.9%) each show a significant yield advantage, and both show higher adjusted odds of on-farm hulling (odds ratios 6.20 and 2.56), so the pooled estimate is not driven by a single organisation type. Because the two member groups are small (22 and 32 farms), they are pooled in the primary models for stability and reported separately only as this sensitivity check.

Two caveats temper this. First, inverse-probability weighting improved but did not fully achieve covariate balance (the largest standardised mean difference fell from 0.85 to 0.31, with residual imbalance on tree count, coffee area and education), so the weighted estimate is treated as supporting rather than primary evidence. Second, E-value analysis [25] shows the two results differ in robustness: an unmeasured confounder would need a risk-ratio association of at least 4.28 with both membership and hulling to nullify the hulling result, but only 2.83 for the yield result—a level that factors such as household wealth or entrepreneurial orientation could plausibly reach. The post-harvest result is therefore more robust to unmeasured confounding than the yield result, and we weight our interpretation accordingly.

Three levels of claim should be distinguished. The survey establishes directly that members out-perform non-members at all three nodes, and that this gap is not explained by farm size, tree count, education, experience, age, extension contact or region. It supports, but does not establish, the interpretation that the shared infrastructure and coordinated extension of producer organisations contribute causally to that gap. A cross-sectional design cannot rule out selection on unmeasured traits, and the yield estimate is sensitive to a moderate confounder. It remains a policy proposition, requiring testing, that expanding

coverage would reproduce these gains among farmers who have not chosen to join. Settling causation would require panel data (each farm serving as its own control) or an exogenous source of variation such as a staged cooperative roll-out unrelated to farmer capability, enabling a difference-in-differences or instrumental-variable estimate. We therefore describe producer-organisation membership as the strongest observed institutional correlate of improved value-chain outcomes and a plausible intervention pathway requiring prospective evaluation, rather than as a demonstrated cause of them.

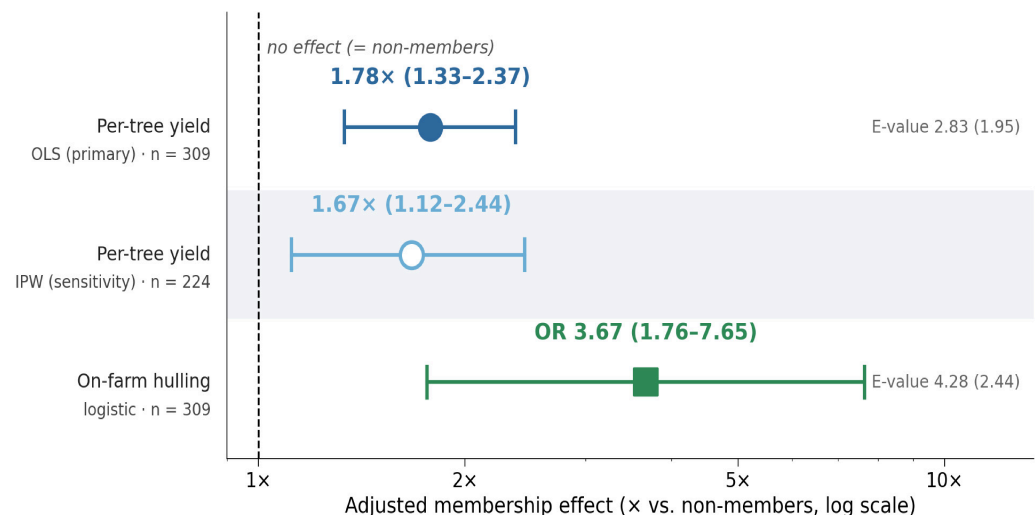


Figure 3. Adjusted associations between producer-organisation membership and value-chain outcomes, on a log scale relative to non-members ($1\times$ = no difference). Per-tree yield is a yield ratio (primary OLS and IPW sensitivity estimates); on-farm hulling is an odds ratio. Models and covariates are described in Section 2.4. E-values (lower confidence limit in parentheses) index robustness to unmeasured confounding—larger values indicate greater robustness.

4. Limitations

This study has five main limitations. First, the cross-sectional design covers only a single production season. Because coffee shows biennial (alternate) bearing, absolute yields can vary between years; but as farms are unlikely to share a synchronised cycle, this affects yield levels more than the cross-cutting relationships that underpin our conclusions. More fundamentally, the design is observational, so none of the associations reported here identifies a causal effect: the adjusted models control for measured confounders only, and the producer-organisation yield estimate would be overturned by an unmeasured confounder of moderate strength (E-value 2.83). Second, most respondents do not keep production records, so yield, area and tree-count variables are recall-based and subject to random measurement error. The patterns reported here, however, are large enough to remain visible despite this noise. Third, the survey did not capture specific agronomic management variables which could explain the residual variation in per-tree yield and are a priority for follow-up study. Fourth, the irrigation sub-survey is restricted to 57 farms in four governorates of Jazan, so its findings cannot be directly extrapolated to Asir or Al Baha. Fifth, the survey covers the three established coffee regions but not the emerging Najran area (under 1% of national production and lacking reliable farmer records in 2023), so the findings are representative of the three main producing regions, which together account for about 99% of national production, rather than of every Saudi coffee producer.

5. Conclusions

Three levels of statement follow from this diagnosis, and we separate them deliberately. What the survey establishes directly is that Saudi Arabia's smallholder Arabica coffee

sector produces well below the per-tree yield its own top decile demonstrates is attainable; that water scarcity is the dominant self-reported production constraint, cited by 84.9% of respondents; that post-harvest practice is weak, with 48.2% of farmers drying on uncovered concrete and no farm in the sample using hermetic storage; that 42.7% of farms sell no coffee at all; and that producer-organisation members out-perform non-members at all three value-chain nodes, a differential that persists after adjustment for farm and farmer characteristics.

What the data support as interpretation, but do not establish, is that the distance between current and attainable yield is institutional, post-harvest and market-structural rather than biological. The absence of a yield return to additional water among Jazan irrigators, together with the cost penalty that additional water carries, is consistent with delivery efficiency, rather than water volume, being the more important lever, a within-sample pattern that would need confirmation in controlled trials. The breadth of the producer-organisation differential is consistent with organisations supplying the shared processing infrastructure, coordinated extension and collective marketing that individual smallholders cannot finance alone. Both readings rest on cross-sectional associations, not causal evidence, and the irrigation evidence is exploratory and confined to Jazan.

The five interventions below are policy propositions that follow from the diagnosis rather than findings the data validate; each would require implementation analysis and, where feasible, prospective evaluation before being taken as established. First, expanding producer-organisation coverage from the current 15% towards one-third of the producer population is the single most promising institutional lever, though the returns observed among current members need not transfer to farmers who have not chosen to join. Second, on the strength of the Jazan evidence, subsidise coffee-customised drip irrigation for demand-matched, night-time delivery, first confirming whether the delivery-efficiency findings transfer to Asir and Al Baha before any national roll-out. Third, combine a targeted integrated pest management programme with active disease surveillance for emerging pathogens. Fourth, build a structured seedling supply chain and broaden extension reach to support sectoral expansion without eroding the genetic integrity of the local landraces. Fifth, invest in post-harvest handling and quality-management systems to protect the value built upstream from quality and food-safety losses.

The findings point to clear potential in the sector. Median per-tree yield is low, yet the top 6.5% of farms already exceed 1 kg per tree, so substantial gains are attainable on existing land. Producer-organisation members also out-performed non-members at all three value-chain nodes. This points to institutional, post-harvest and market-structural constraints rather than agronomic limits. Output could rise through two routes: higher per-tree yield and a larger planted area. The national tree and seedling figures in Section 3.1.2 are indicative ranges from self-reported data, best read as planning scenarios for evaluation rather than validated projections. Whether producer-organisation membership causally improves performance is the most tractable question for future work. A staged expansion of coverage, with the roll-out order recorded and a baseline collected beforehand, would provide the natural experiment needed to answer it. We identify this as our priority for follow-up research.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16151689/s1>, Section S1: Analytical sample and missing data; Section S2: Membership-selection model (who becomes a member); Table S1: Logistic model of producer-organisation membership ($n = 347$; McFadden pseudo- $R^2 = 0.218$; reference outcome = non-member); Section S3: Covariate balance before and after weighting; Table S2: Standardised mean differences (SMD) between members and non-members before and after inverse-probability weighting; Section S4: Adjusted per-tree-yield model (primary estimate); Table S3: Ordinary least-squares model of log per-tree yield with HC1 robust standard errors ($n = 309$; $R^2 = 0.127$);

Section S5: Adjusted on-farm-hulling model; Table S4: Logistic model of mechanised on-farm hulling ($n = 309$; McFadden pseudo- $R^2 = 0.152$); Section S6: Inverse-probability-weighted estimate (yield); Section S7: By-organisation-type sensitivity (association vs. cooperative); Table S5: Adjusted associations estimated separately for association and cooperative members (reference = non-members; same covariates as Tables S3 and S4); Section S8: E-value sensitivity to unmeasured confounding; Table S6: E-values for the adjusted associations; Section S9: Validation of the statistical implementation; Table S7: Validation of each statistical routine against a known reference value (all pass).

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Institutional Review Board Statement: The survey was conducted under the SRAD Programme protocols. It was approved by the implementing partners (FAO and MEWA). The work involved standard household-survey enumeration and complied with the Helsinki Declaration's principles for research involving human subjects.

Informed Consent Statement: The survey was conducted under the SRAD Programme (FAO and MEWA). Verbal informed consent was obtained from every respondent. Names and personal contact details were not reported.

Data Availability Statement: The main survey and the irrigation survey datasets are available from the corresponding author on reasonable request. Release is subject to permissions from MEWA and FAO. The analysis code and its validation suite, which reproduce the reported statistics, are available from the corresponding author on reasonable request.

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