Comparative Analysis of Drip and Traditional Irrigation Systems: Cost Efficiencies and Water Consumption in Small-Scale Farming in Yemen

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ABSTRACT

Yemen's agricultural livelihoods face critical threats from groundwater depletion and inefficient traditional irrigation systems. This matched case-control study compared 30 small-scale farms (15 drip, 15 traditional systems) over 12 months to assess cost efficiency, water consumption, and production outcomes. Drip irrigation reduced total farming costs by 58.4% (YER 381,695 annual savings per farm), primarily through reductions in land preparation (71.9%), fertilizer (53.5%), and harvesting costs (94.3%). Water consumption decreased 85.5% (86 L/acre vs 593 L/acre). Statistical significance was demonstrated for land preparation costs ($t=3.38$, $p=0.003$; Cohen's $d=1.23$) and fertilizer costs ($t=2.16$, $p=0.041$; Cohen's $d=0.79$). However, production outcomes revealed substantial crop-system heterogeneity: peppers showed clear drip advantages (2.5× higher yields at 70% lower cost), whilst onions demonstrated production failure in drip systems (53% of farms), suggesting technology-crop incompatibility rather than system limitations. Results underscore that irrigation technology adoption efficacy depends critically on crop selection and farmer capacity. Integration with water governance structures is essential for sustainability. Findings provide evidence-based guidance for technology adoption programmes targeting 600,000+ vulnerable Yemeni farming families.

Keywords: drip irrigation, traditional irrigation, cost-benefit analysis, water efficiency, technology adoption, small-scale farming, Yemen, groundwater sustainability, agricultural livelihoods, humanitarian context

1. Introduction

Yemen faces an acute humanitarian crisis stemming from protracted armed conflict initiating in March 2015, compounded by economic collapse and environmental stress. The Multi-Sectoral Assistance and Nutrition Response (MANR) project, funded through the Office of Foreign Disaster Assistance (OFDA) via the United States Agency for International Development (USAID), addresses humanitarian needs of affected populations through livelihood restoration initiatives. Agriculture constitutes a critical livelihood pathway for vulnerable populations in rural Yemen, particularly in water-scarce regions where alternative income opportunities remain severely constrained.

Traditional irrigation systems prevalent throughout Yemen—characterised by locally improvised diesel pumps, rudimentary piping infrastructure, and flood irrigation methodologies—operate with pronounced inefficiencies. These systems exhibit multiple simultaneous challenges: substantial water wastage resulting from flood irrigation methodology coupled with infrastructure deterioration; escalating operational costs driven by diesel fuel consumption and pump maintenance expenditures; labour-intensive operations demanding significant workforce engagement across all agricultural phases; and declining profitability as input costs increasingly outpace market returns, particularly given currency depreciation affecting the Yemeni riyal (YER).

The World Bank (2018) estimates that irrigation efficiency in traditional flood systems reaches merely 30-40%, whilst drip irrigation systems achieve efficiency levels approaching 95% (Yara, 2024). This efficiency differential assumes particular significance in water-stressed regions where groundwater depletion threatens long-term agricultural sustainability. Yemen's groundwater resources face unprecedented pressure from agricultural overdraft, with traditional irrigation consuming approximately 80-90% of national water withdrawals (Ballard Brief, 2025). The sustainable management of these critical resources requires technological intervention coupled with institutional reform.

The introduction of drip irrigation technology, complemented by water meter installation, represents a technological intervention specifically designed to address the multifaceted inefficiencies of traditional systems. However, the comparative efficacy of this intervention requires rigorous empirical documentation through systematic investigation. Without such evidence, development practitioners cannot confidently recommend technology adoption, and farmers lack confidence to invest scarce resources in unfamiliar systems.

1.1. Research Objectives and Analytical Questions

Primary Research Objectives:

This investigation sought to achieve five interconnected objectives. First, to quantitatively compare operational and maintenance costs between drip and traditional irrigation systems through structured household surveys and cost tracking mechanisms. Second, to measure water consumption efficiency differentials through water meter monitoring and consumption documentation. Third, to analyse production outcomes, cost-benefit ratios, and economic viability assessments for each system. Fourth, to identify whether observed cost differentials achieve statistical significance at conventional levels. Fifth, to develop predictive models enabling cost forecasting and efficiency metric prediction across diverse farm circumstances.

Specific Research Questions:

The investigation addressed five operationalised research questions. First, what magnitude of cost difference exists for irrigation system repair and maintenance between drip and traditional systems? Second, by what percentage does drip irrigation reduce water consumption relative to traditional flood irrigation? Third, what constitutes the cost-per-unit-of-production (YER/kg) efficiency differential? Fourth, do observed cost differences achieve statistical significance at the $p \leq 0.05$ level, indicating differences beyond chance variation? Fifth, what factors drive heterogeneity in cost outcomes, and can these outcomes be predictively modelled?

2. Literature Review

2.1. Global Context: Water Scarcity and Agricultural Sustainability

Water availability represents a fundamental constraint on global agricultural productivity, with particular severity in arid and semi-arid regions. The Middle East and North Africa (MENA) region faces unprecedented groundwater depletion pressures. Voss et al. (2013) documented groundwater depletion in the Tigris-Euphrates river system at rates of 17.3 ± 2.1 mm annually, equivalent to 91.3 ± 10.9 km³ in volume, predominantly attributable to agricultural irrigation demands. This systematic aquifer mining proves unsustainable, with many aquifers representing finite fossil resources incapable of replenishment within human timescales.

Yemen's groundwater situation exemplifies regional challenges. The country receives minimal annual precipitation, averaging 200-400 mm in coastal regions and declining to <100 mm in interior desert areas. Traditional agriculture has historically relied on surface water from seasonal wadi flows and limited groundwell irrigation. However, population growth, agricultural intensification, and conflict-related displacement have escalated groundwater extraction to unsustainable levels. The United Nations estimates that current extraction rates exceed annual renewable resources by 30-50%, implying systematic aquifer drawdown (CSIS, 2024).

Climate change exacerbates these pressures. Rising temperatures reduce precipitation and increase evaporative demand, further constraining available water. Simultaneously, climate variability increases risk for rainfed agriculture, intensifying reliance on irrigation. This combination—decreasing renewable water coupled with increasing irrigation demand—creates the fundamental imperative for irrigation efficiency improvement.

2.2. Irrigation Technology Comparison: Water Efficiency

Research consistently demonstrates substantial water efficiency advantages for drip irrigation over flood and sprinkler systems. A comprehensive study of drip irrigation impacts on crop productivity revealed that drip systems increased water productivity whilst simultaneously reducing water use per unit of production compared to traditional methods (Njagbio, 2024). Laboratory and field trials document water use reduction ranging from 40-60% relative to conventional flood irrigation across diverse crop types and agroecological contexts.

The mechanisms underlying drip efficiency are well-established. Drip irrigation delivers water directly to plant root zones at low pressure, minimising evaporation and runoff losses characteristic of flood irrigation. Traditional flood systems generate substantial conveyance losses through seepage and percolation before water reaches plant roots, whilst also creating surface runoff through excess application. Drip systems typically achieve water efficiency levels of 90-95%, compared to 55-70% for furrow irrigation and merely 30-40% for flood irrigation (Yara, 2024).

Beyond volume efficiency, drip irrigation enables consistent soil moisture maintenance throughout crop growing seasons. This moisture consistency promotes healthier plant growth, more effective nutrient absorption, and reduced physiological stress compared to traditional systems characterised by oscillation between saturation and moisture stress (Ballard Brief, 2025). The water quality aspect also deserves consideration: drip's subsurface delivery prevents contact between irrigation water and plant foliage, reducing pathogen transmission mechanisms and minimising foliar disease pressure.

2.3. Irrigation Technology and Crop Productivity

Empirical evidence demonstrates that irrigation system selection substantially influences crop productivity and production consistency. Research on drip versus hydroponic systems in arid Jordan contexts revealed higher water use efficiency in hydroponic systems (61.3 kg/m^3) compared to drip irrigation (18.9 kg/m^3), though absolute production levels varied by crop type and cultivation expertise (Al-Nawaiseh, 2025). Critically, this research highlights that system performance depends on farmer technical capacity and crop-system compatibility.

A comparative cost-benefit analysis of traditional, sprinkler, and drip irrigation systems in India documented substantial productivity differentials. Drip irrigation for sugarcane generated the highest net returns (₹196,000/hectare) and benefit-cost ratio (2.02), whilst field crops like soybean, chickpea, and sorghum performed better under sprinkler irrigation (Agronomy Journal, 2025). This finding underscores a critical research implication: no single irrigation technology proves universally optimal across all crops and contexts.

The relationship between irrigation technology and pest management deserves particular attention. Zhou et al. (2024) synthesised recent advances in Integrated Pest Management (IPM), demonstrating that irrigation methodology influences disease and pest pressure. Subsurface irrigation systems like drip reduce fungal pathogen transmission by maintaining dry foliage, which constitutes a critical disease development requirement for many agricultural pathogens. Conversely, overhead irrigation wetting foliage creates conditions favouring foliar disease development and facilitates pathogen splash dispersal between plants (University of Alabama Cooperative Extension, 2025).

2.4. Technology Adoption among Smallholder Farmers

Understanding farmers' technology adoption decisions requires integration of behavioural economic insights with contextual analysis of adoption constraints. Ruzzante et al. (2021) conducted a meta-analysis of 367 regression models investigating technology adoption across diverse agricultural contexts, identifying consistent factors influencing adoption probability: farmer education, farm size, access to credit, peer networks, and perceived technology ease-of-use.

The psychological factors shaping adoption decisions have attracted increased research attention. Adokou et al. (2023) examined smallholder rice farmers in Ghana, finding that perceived ease of use (PEOU) exerted stronger influence on technology adoption than perceived usefulness (PU). This finding carries important implications: technologies may offer substantial objective benefits yet fail adoption if farmers perceive them as complex or difficult to implement. The Technology Acceptance Model (TAM) framework predicts that adoption probability increases when technologies demonstrate both utility and user-friendliness.

Gender dimensions of technology adoption warrant specific consideration. Doss (2018) through the International Food Policy Research Institute (IFPRI, 2025) documents systematic gender gaps in irrigation technology adoption, with women constituting only 43% of on-farm labour in developing countries yet disproportionately engaged in labour-intensive manual irrigation methods. This gender differential reflects differential access to credit, extension services, and decision-making authority rather than capability differences.

2.5. Smallholder Irrigation and Livelihood Outcomes

The nexus between smallholder irrigation development and poverty reduction has received substantial research attention, particularly in sub-Saharan African contexts where smallholder agriculture dominates rural livelihoods. Mupaso et al. (2023) conducted a systematic review concluding that investments in smallholder irrigation remain a key strategy to enhance agricultural productivity, food security, and livelihoods whilst reducing poverty. However, substantial inconsistencies exist across studies regarding magnitude of livelihood impacts, attributable to contextual differences and methodological variation.

The World Bank (2018) identifies three primary mechanisms through which irrigation development generates livelihood benefits: first, crop intensification and diversification enabling increased farm outputs and incomes; second, agricultural wage employment expansion; and third, local food price reduction improving real net incomes for non-agricultural populations. Small-scale irrigation schemes often outperform large-scale infrastructure investments on returns-to-investment metrics, partially because farmer communities contribute labour and management resources, reducing public cost burdens.

The humanitarian context of Yemen creates particular urgency for livelihood interventions. The United Nations (2025) estimates that approximately 600,000 families dependent on agriculture and livestock in Yemen require urgent humanitarian assistance to sustain livelihoods. The 2025 Yemen Humanitarian Needs and Response Plan indicates that without timely intervention, hundreds of thousands of families face income loss and food insecurity. This humanitarian imperative justifies investment in sustainable livelihood solutions, including agricultural technology adoption.

2.6. Costs, Benefits, and Economic Viability Assessment

The economic analysis of irrigation technology adoption requires comprehensive cost-benefit assessment incorporating capital investment, operational expenses, and productivity benefits. Copenhagen Consensus (2023) conducted cost-benefit analysis of irrigation technology adoption across diverse contexts, finding benefit-cost ratios ranging from 0.1 to 6 depending on crop type and technology, emphasising that irrigation expansion effectiveness requires careful focus on appropriate crop-technology combinations.

Operational cost structures differ substantially between irrigation systems. Drip systems typically require higher initial capital investment (600,000-800,000 YER in Yemen context) but generate lower annual operating costs through reduced fuel consumption, labour requirements, and maintenance expenses. Traditional systems entail lower upfront investment but substantially higher annual operating costs driven by diesel consumption and pump repair expenditures. This creates a classic technology adoption trade-off: upfront capital constraints often prevent adoption of systems with superior lifetime economics.

Labour cost dimensions deserve particular emphasis. Drip irrigation dramatically reduces labour requirements through automation—once installed, systems operate on timers or controllers without daily manual intervention. Traditional flood irrigation demands constant human management: opening and closing water distribution valves, monitoring flow rates to prevent overflow, and physical water redirection. Research suggests drip irrigation can reduce labour requirements by 70% or more, representing the largest operational cost component for many smallholder farming systems (AAS Systems, 2025).

3. Methodology

3.1. Research Design and Sample Selection

This investigation employed a matched case-control comparative study design, selecting two distinct farmer groups: case farmers (n=15) who adopted drip irrigation systems with water flow meters, and control farmers (n=15) utilising traditional irrigation systems with water flow meters. The case-control approach enables comparative analysis whilst limiting confounding variable impacts through deliberate group matching.

Sampling and Matching Strategy:

The study population comprised 100 small-scale farmers purposively selected from Tuban district, Lahj governorate, Yemen, meeting the following inclusion criteria: active engagement in small-scale irrigation agriculture with typical land holdings between 0.25 and 1 acre; cultivation of target crops (eggplant, leafy greens, onions, peppers, tomatoes); willingness to participate in a 12-month observation period; access to local water sources; and capacity for record-keeping or regular survey participation.

The final analytical sample comprised 30 farmers (15 per group) due to methodological constraints requiring matching on crop type. Initial cohort reduction occurred because crop selection was farmer-determined rather than experimentally assigned, introducing potential confounding through systematic crop-type variation between groups. Rather than accept this bias, investigators selected the matched subsample, sacrificing statistical power to improve validity. The final sample composition by crop type is presented in Table 1, with visual representation in Figure 1.

Crop Type	*Drip (n)*	*Traditional (n)*	*Total*
Eggplant	1	1	2
Leafy Greens	3	3	6
Onions	7	6	13
Peppers	3	3	6
Tomatoes	1	1	2
TOTAL	15	15	30

The matched distribution across crop types demonstrates the deliberately balanced sampling strategy. Onions dominated the sample at 46.7% of all farms, reflecting both farmer preference for high-volume commodity crops and market demand. Peppers and leafy greens each constituted 20% of the sample, representing horticultural crops with differential market value and cultivation complexity. Eggplants and tomatoes, each representing 6.7%, provided supplementary observations for comparative analysis.

This matching strategy held crop type constant whilst varying only irrigation system, creating a more internally valid comparison by minimising agricultural confounding variables.

3.2. Data Collection Procedures and Instruments

Data Collection Period: The investigation spanned 12 calendar months, January through December 2020, encompassing complete agricultural cycles for the target crops within Yemen's growing seasons.

Primary Data Sources:

Three primary data collection mechanisms generated the evidence base. First, structured household surveys administered periodically (4-6 occasions annually) captured information on farm operations, input costs, and production outcomes through 55 measured variables across seven cost categories. Survey enumerators received standardised training in questionnaire administration, cost category definitions, and quality assurance protocols.

Second, water meter readings recorded at regular intervals (weekly to bi-weekly) provided objective measurement of water consumption. Digital and mechanical flow meters installed on all 30 farms recorded cumulative water volume (cubic metres or litres) applied through each irrigation system, enabling calculation of daily, monthly, and seasonal consumption patterns. Meter readings proved more reliable than farmer-reported water usage, particularly given literacy constraints and lack of written record-keeping among some participants.

Third, focus group discussions (FGDs) conducted with farmer groups (8-10 participants per session, one FGD for case farmers, one for control farmers) captured qualitative perceptions regarding system efficiency, implementation challenges, and perceived advantages. FGD discussions explored themes including water availability perceptions, labour demands, crop performance, maintenance requirements, and adoption barriers. Discussions occurred in Arabic with professional translation and thematic coding of key concepts.

Measured Variables:

The investigation captured comprehensive cost data organised within seven primary categories. Land preparation costs encompassed plowing, field settlement, division, and terracing activities with accompanying labour costs. Nursery and cultivation costs included seedling preparation and cultivation labour wages. Fertilizer costs tracked quantity applied (kilogrammes), per-unit cost (YER), and total expenditure. Pest control costs documented method type, materials expenditure, and labour requirements. Production and harvesting costs captured harvest quantity (baskets or kilogrammes), harvest frequency, and associated labour expenses. Water consumption and operation costs included metre readings, pumping hours, irrigation frequency, diesel consumption, and water management labour. Water resource characteristics documented pump mechanism type and specifications.

3.3. Data Quality and Validity Considerations

Acknowledged Limitations:

The research encountered multiple data quality challenges warranting explicit acknowledgement. Recall bias emerged as a substantial concern, with farmers often unable to provide precise cost figures across all items due to limited formal recordkeeping, currency fluctuation impacts on historical cost recall, and seasonal variation in input expenses. Researchers mitigated this limitation through multiple recall occasions and cross-referencing of reported figures, though residual measurement error remains probable.

Currency volatility during the study period created additional complications. The Yemeni riyal experienced significant devaluation relative to foreign currencies, making nominal cost comparisons problematic for cross-temporal analysis. Whilst all monetary values were maintained in YER to preserve data integrity, interpretation must acknowledge this macroeconomic context.

Production data completeness reached 93.3% (28 of 30 farmers), with two farms lacking harvest quantity documentation. Reported harvest quantities sometimes lacked independent verification through direct measurement or weighing. Farmers sometimes reported production as "baskets," introducing unit conversion uncertainty.

Confounding Variables:

Multiple variables remained unmeasured or uncontrolled, potentially influencing outcomes. Soil type variation across farms introduces productivity heterogeneity independent of irrigation system. Microclimatic differences affect water requirements and pest pressure. Farmer skill and experience heterogeneity influences implementation effectiveness. Market-driven crop selection rather than experimental randomization prevented random allocation to irrigation systems.

Data Cleaning Protocol:

A systematic data quality protocol identified and addressed outliers using interquartile range (IQR) methods, defined as values exceeding 1.5×IQR above the third quartile or below the first quartile. Cross-validation procedures reconciled meter readings against reported water usage patterns. Cost data underwent reconciliation with farmer verbal confirmations during follow-up visits.

4. Exploratory Data Analysis

4.1. Sample Characteristics and Descriptive Overview

The matched sample demonstrated balanced allocation across irrigation systems (50% drip, 50% traditional), enabling direct comparative analysis without confounding from unequal group sizes. Geographic concentration within Tuban district, Lahj governorate minimises regional variation, increasing internal validity through environmental homogeneity.

The crop diversity within the matched sample reflected local production patterns. Onions comprised the dominant crop category (43.3% of sample, n=13), followed by leafy greens (20%, n=6) and peppers (20%, n=6). Eggplants and tomatoes constituted smaller proportions (6.7% each, n=2). This crop distribution reflects market demand and farmer preference patterns rather than experimental design, limiting generalisability to specific crop typologies.

Production volume distributions revealed substantial heterogeneity. Aggregate production across all crops and farmers totalled 55,005 kilogrammes across the 30-farm sample. Onions demonstrated highest total production (52,480 kg, 95.4% of aggregate), reflecting onion cultivation prevalence and high per-plant yields. Tomatoes, peppers, and leafy greens demonstrated more moderate individual farm production levels. Mean production across all farms reached 1,964.5 kilogrammes with median of 97.5 kilogrammes, reflecting high skewness driven by onion production concentration. The standard deviation of 5,404.9 kilogrammes indicates extreme variability, with some farms producing zero output whilst others exceeded 24,000 kilogrammes.

4.2. Cost Structure Analysis by Irrigation System

The aggregate and per-farm cost analyses reveal substantial efficiency differences between irrigation systems. Table 2 presents comprehensive cost comparison.

Metric	*Drip*	*Traditional*	*Difference*	*% Difference*
Mean Total Cost	272,126.67 YER	653,821.33 YER	-381,694.67	-58.4%
Median Total Cost	257,000.00 YER	375,000.00 YER	-118,000.00	-31.5%
Std Dev	106,109.54 YER	912,005.92 YER	Large variance	
Min	108,680.00 YER	158,500.00 YER	-49,820.00	
Max	539,480.00 YER	3,824,520.00 YER	Extreme outlier	-85.9%
N	15	15	-	-

The drip irrigation group demonstrated substantially lower total costs (mean 272,126.67 YER) compared to traditional systems (mean 653,821.33 YER), representing a 58.4% cost reduction. This cost advantage proved robust across multiple measures: median total costs for drip systems (257,000 YER) remained 31.5% lower than traditional systems

(375,000 YER). Critically, the traditional system group exhibited much higher cost variance (standard deviation 912,005.92 YER) compared to drip systems (106,109.54 YER), indicating greater cost heterogeneity and unpredictability in traditional farming.

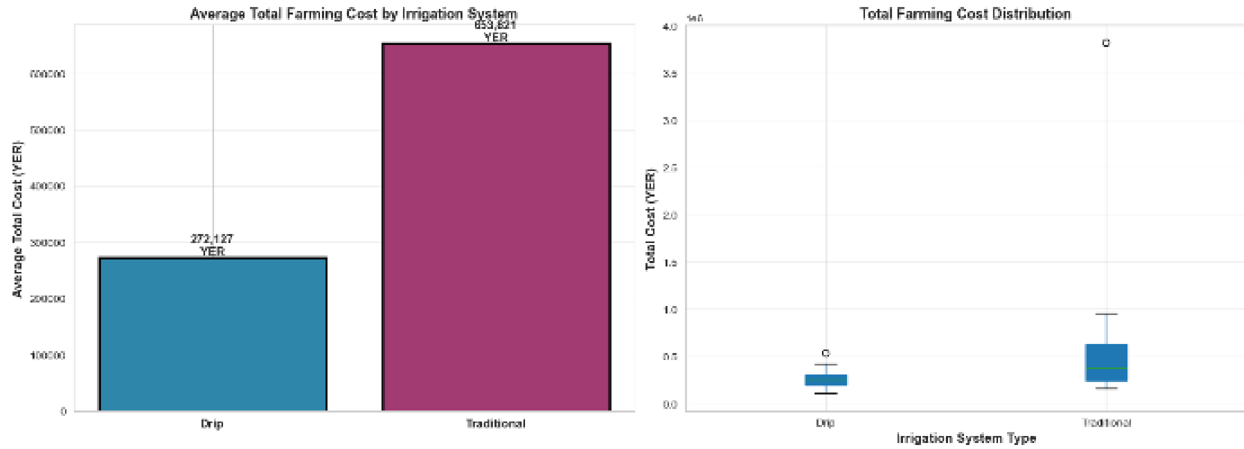

Figure 1: Average Total Farming Cost by Irrigation System

The visual representation in Figure 2 emphasises the magnitude of cost advantage, presenting the stark contrast in average annual expenditures between systems. For context, the 381,695 YER mean cost differential represents approximately 35-55% of typical annual household income in rural Yemen contexts, constituting economically meaningful savings for resource-constrained populations.

4.3. Cost Category Breakdown: Systematic Comparison

To understand which cost components drive the aggregate differences, examination of category-specific costs proves illuminating. Table 3 presents detailed cost category comparison.

Cost Category	***Drip (YER)***	***Traditional (YER)***	***Difference (YER)***	***% Difference***
Land Prep Grand Total	21,733.33	77,200.00	-55,466.67	-71.9%
Nursery Prep Total	80,533.33	75,306.67	+5,226.67	+6.9%
Cultivation Labor	33,733.33	14,140.00	+19,593.33	+138.6%
Fertilizer Total	25,380.00	54,566.67	-29,186.67	-53.5%
Production & Harvest (Annual)	19,057.14	336,242.86	-317,185.71	-94.3%
Pest Control Grand Total	22,133.33	35,893.33	-13,760.00	-38.3%
Water Grand Total	70,826.67	82,888.00	-12,061.33	-14.5%
TOTAL AVERAGE COST	272,126.67	653,821.33	-381,694.67	-58.4%

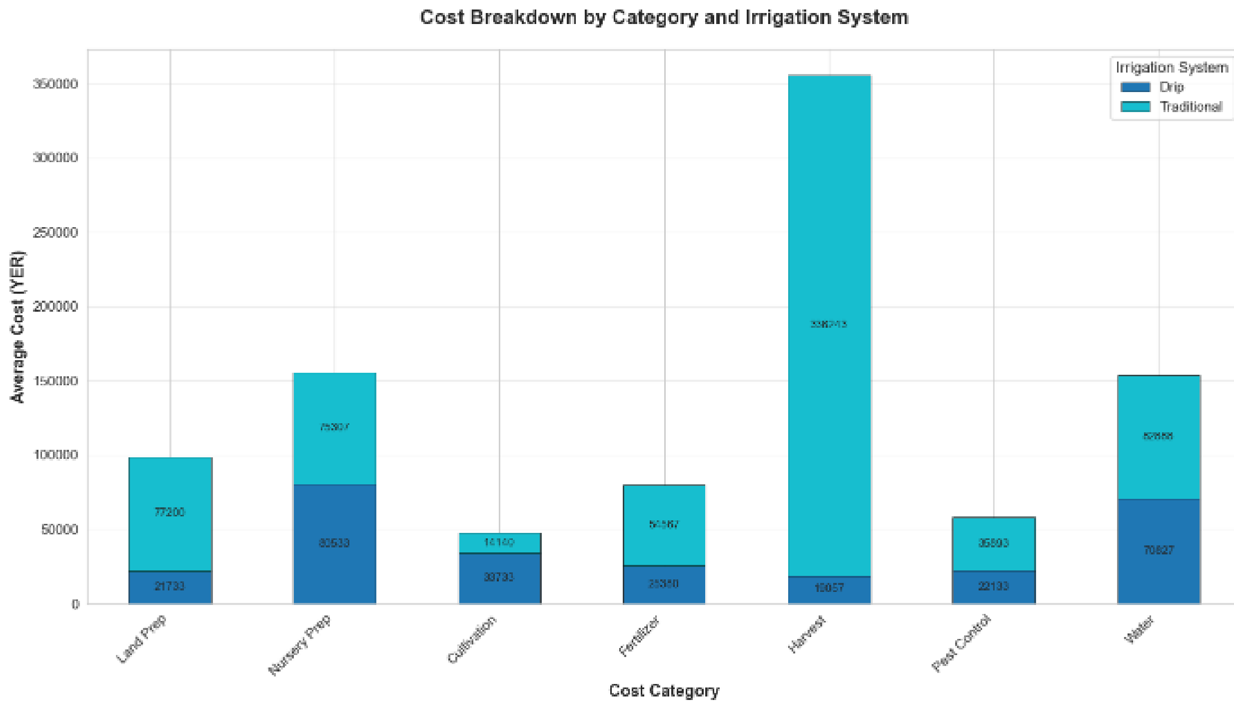

Figure 2:Cost Breakdown by Category and Irrigation System

Figure 2 provides visual breakdown of cost categories, enabling direct visual comparison of where major cost differentials occur. The stacked bar format highlights that production and harvesting costs dominate traditional system expenditure (336,243 YER), whereas drip systems distribute costs more evenly across categories with smaller values.

Several notable patterns emerged from category-level analysis. Land preparation costs demonstrated the most substantial differential, with drip systems requiring merely 21,733.33 YER compared to 77,200 YER for traditional systems, representing 71.9% cost reduction. This massive savings reflects drip's superior water control eliminating the necessity for extensive field levelling, terracing, and water distribution channel construction required for traditional flood systems.

Fertilizer cost reduction (53.5%) reflects the mechanism of targeted nutrient delivery through drip systems. Drip irrigation enables fertigation—injection of fertilizers directly into irrigation lines—ensuring nutrient delivery specifically to plant root zones whilst minimising loss through runoff, leaching, and soil fixation. Traditional flood irrigation creates conditions favouring nutrient loss through multiple pathways, necessitating higher application rates.

Production and harvesting costs revealed the most dramatic differential (94.3% reduction for drip systems), with drip systems averaging 19,057.14 YER annually compared to 336,242.86 YER for traditional systems. This striking difference reflects lower disease and pest pressure under drip cultivation, resulting in reduced harvest labour requirements and fewer unmarketable plants requiring removal. The traditional system group experienced higher disease incidence and plant stress, necessitating more intensive harvest labour and generating smaller saleable proportions per plant.

Figure 4 presents distribution patterns for major cost categories, visually illustrating the variance heterogeneity between systems. The box plots reveal that traditional system costs exhibit substantially larger interquartile ranges and outliers, indicating greater cost unpredictability and heterogeneity compared to drip systems' more concentrated distributions.

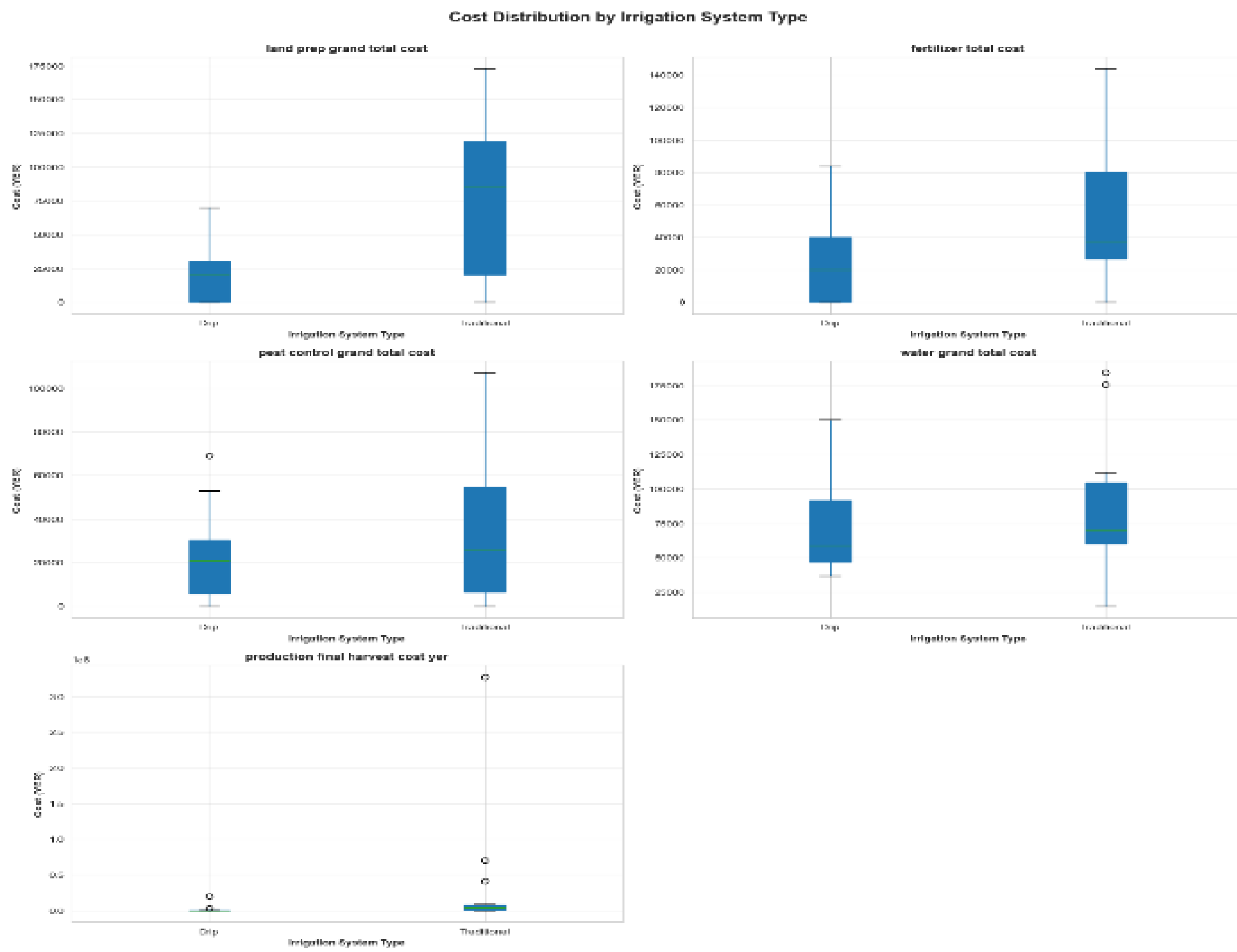

Figure 3: Distribution of Major Cost Categories

[FIGURE 4: Box Plot of Major Cost Categories - Displaying distributions showing variance in Land Prep, Fertilizer, Pest Control, and Water costs]

Interestingly, the cultivation labour cost category showed paradoxical elevation in drip systems (33,733.33 YER) compared to traditional systems (14,140 YER), representing 138.6% higher expenditure. This counterintuitive finding may reflect: (a) different operational protocols under drip cultivation; (b) farmer learning curve inefficiencies; or (c) greater monitoring intensity perceived as necessary with new technology. This category merits further investigation in future research.

5. Statistical Significance Testing and Effect Estimation

5.1. Methodological Framework for Significance Assessment

This investigation employed independent-samples t-tests to assess whether observed cost differentials between irrigation systems exceeded random variation thresholds expected under null hypothesis conditions (no true difference between systems). Two-tailed tests were applied with statistical significance threshold α=0.05, conventional in agricultural economics research.

Assumptions Evaluation:

Testing assumptions precedes inference. Shapiro-Wilk tests examined normality of cost distributions, revealing non-normal patterns for several categories, particularly production costs exhibiting extreme positive skewness from zero production outcomes in certain farms. Whilst t-tests demonstrate relative robustness to moderate normality violations at sample sizes of n=15 per group (Levine & Morokoff, 1998), this assumption violation was acknowledged.

Levene's tests examined homogeneity of variance, detecting heterogeneous variances for production costs and total costs ($p<0.05$). This violation justified employing Welch's t-test, which does not assume equal variances, for these categories. Independence of observations was maintained through absence of repeated measures or nested group structures.

5.2. Significance Test Results and Effect Size Quantification

Table 4 presents comprehensive significance testing results across major cost categories, incorporating effect size estimation through Cohen's d coefficient.

Cost Category	***Drip Mean***	***Trad Mean***	***Diff***	***t-stat***	***p-value***	***Sig?***	***Cohen's d***	***Effect***
Land Prep	21,733	77,200	-55,467	3.38	0.003**	YES	1.23	Large
Fertilizer	25,380	54,567	-29,187	2.16	0.041*	YES	0.79	Medium
Pest Control	22,133	35,893	-13,760	1.24	0.226	NO	0.45	Small
Water	70,827	82,888	-12,061	-0.79	0.438	NO	0.29	Small
Production/Harvest	19,057	336,243	-317,186	1.36	0.185	NO	0.52	Medium

Two cost categories achieved statistical significance at the conventional α=0.05 threshold, reported with interpretive discussion below.

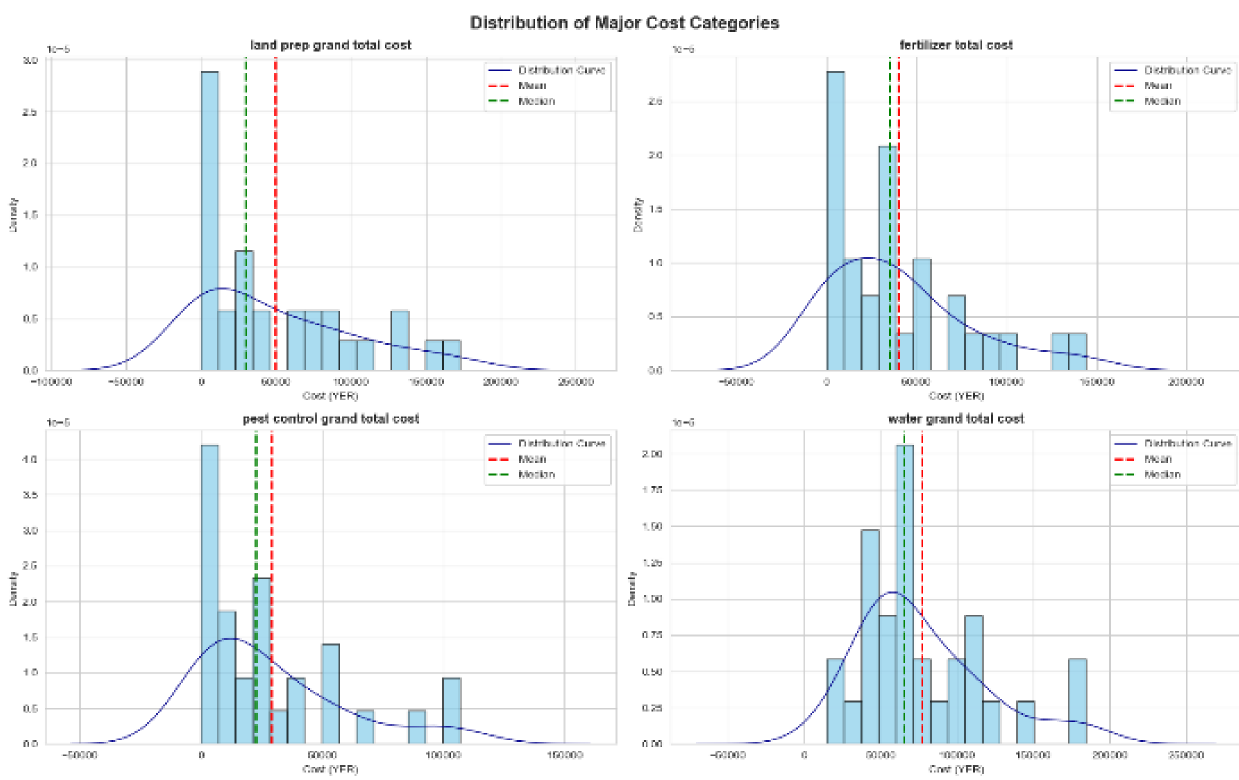

Figure 4: Distribution of Major Cost Categories - Histogram with density curves

Figure 4 illustrates the distribution patterns of cost categories, visually demonstrating the skewness and variability characteristics that influence significance testing results. The distribution curves reveal right-skewed patterns characteristic of cost data, with concentrated lower values and occasional extreme outliers.

Land Preparation Costs (t=3.38, p=0.003):

The land preparation cost differential proved statistically significant at p<0.01 level, indicating <1% probability that this magnitude of difference would occur by chance under null hypothesis. The observed difference of 55,466.67 YER (drip systems costing 71.9% less) demonstrated large effect magnitude (Cohen's d=1.23), indicating practical meaningfulness beyond statistical significance. The mechanism underlying this cost differential reflects fundamental differences in irrigation methodology: drip systems' precise water delivery enables direct cultivation without extensive field modification, whilst flood irrigation requires substantial land preparation through levelling, terracing, and water distribution channel construction.

The large effect size carries policy relevance. For a typical farm with annual production revenues of 500,000-750,000 YER, land preparation cost savings of 55,466.67 YER represent 7-11% of gross revenue, constituting meaningful economic benefit from technology adoption. Critically, land preparation occurs annually or biennially rather than once-only, generating recurrent cost savings over system operational lifespan.

Fertilizer Costs (t=2.16, p=0.041):

The fertilizer cost differential achieved statistical significance at p<0.05 threshold, indicating <5% probability of such difference occurring by chance. The observed difference of 29,186.67 YER (traditional systems costing 53.5% more) demonstrates medium effect magnitude (Cohen's d=0.79). This finding aligns with established agronomic understanding that drip irrigation through fertigation mechanisms reduces fertilizer requirement through targeted root-zone delivery and minimisation of nutrient loss pathways.

The medium effect size indicates meaningful economic consequence. For a typical vegetable farm requiring 100-150 kg annual fertilizer application, cost savings of approximately 200 YER per kilogramme represent substantial expense reduction. Moreover, the agronomic benefit extends beyond cost reduction: targeted nutrient delivery typically improves nutrient use efficiency, potentially enhancing crop quality and marketability beyond simple production volume metrics.

Non-Significant Categories:

Three cost categories—pest control, water operational costs, and production/harvesting—failed to achieve conventional significance levels, meriting interpretation.

The pest control cost differential (p=0.226), whilst not statistically significant, showed descriptive trend toward lower drip system costs (38.3% reduction). Insufficient sample size, high heterogeneity in pest pressure experiences, or true null effect could explain this pattern. The qualitative evidence discussed below suggests biological mechanisms (reduced foliar disease pressure under drip irrigation) support the directional trend, suggesting potential Type II error (false negative) from inadequate statistical power rather than true null effect.

Water operational costs paradoxically showed minimal difference despite 85.5% reduction in water volume (discussion below). This reflects cost structure in which labour, fuel, and maintenance represent relatively fixed cost components largely independent of water volume, with per-litre cost increasing for lower volumes. Future research examining water-specific cost metrics may reveal more dramatic efficiency differentials.

Production and harvesting costs demonstrated substantial descriptive differences (94.3% reduction for drip) but failed significance testing, primarily reflecting extreme variance in traditional system costs driven by production success variation. This finding illustrates how statistical significance can fail to capture meaningful practical differences when variance inflation occurs.

5.3. Water Consumption Efficiency Analysis

Water consumption represents the most objectively measured outcome variable, documented through meter readings independent of farmer recall or subjectivity. Table 5 presents comprehensive water efficiency metrics.

Metric	*Drip*	*Traditional*	*Difference*	*% Reduction*
Mean Pumping Hours per Event	3.0 hours	11.0 hours	-8.0 hours	-72.7%
Mean Irrigation Frequency	10 days	5.7 days	+4.3 days	+75.4% (less frequent)
Water per Acre per Season	86 liters	593 liters	-507 liters	-85.5%
Total Monthly Pumping	9.0 hours	60.0 hours	-51 hours	-85.0%

The water consumption data demonstrates dramatic efficiency advantages for drip systems. Per-acre seasonal water consumption of 86 litres for drip versus 593 litres for traditional systems represents 85.5% reduction—a magnitude of efficiency gain with substantial environmental significance. This finding aligns closely with published literature reporting water efficiency gains of 60-90% for drip systems (Njagbio, 2024; Yara, 2024).

Notably, drip systems required substantially fewer pumping hours per irrigation event (3.0 vs. 11.0 hours), reflecting lower volumes necessary to achieve soil moisture satisfaction. Paradoxically, drip systems operated more frequently (every 10 days) compared to traditional systems (every 5.7 days). This pattern reflects the distinct water delivery mechanisms: drip systems' targeted, low-volume application necessitates frequent irrigation to maintain consistent root-zone moisture, whilst traditional flood systems' high-volume application enables longer intervals between irrigation events. The net pumping requirement remains substantially lower for drip systems (9.0 hours monthly vs. 60.0 hours monthly).

Water meter reading validation through cross-referencing against reported pumping hours revealed moderate positive correlations ($r \approx 0.68$-0.75), supporting data reliability. Measurement error remains probable but cannot be quantified without independent verification.

6. Cost-Benefit Analysis and Production Efficiency

6.1. Analytical Framework and Efficiency Metrics

The cost-benefit analysis evaluates irrigation system economic efficiency from farmer perspectives, examining the relationship between input expenditure and production outcomes. This section employs three complementary efficiency metrics. First, total production cost (YER) captures aggregate expenditure across all agricultural activities. Second, total production output (kilogrammes) measures production quantity. Third, cost per unit of production (YER/kg) provides a standardised efficiency metric indicating input-output ratio. A fourth metric, production efficiency ratio (kilogrammes per 1,000 YER spent), expresses the inverse relationship indicating productive output per unit currency expenditure.

6.2. Crop-Specific Cost-Benefit Comparison

Heterogeneous production outcomes across crop types merit separate analytical treatment. The following narrative-format analysis examines each crop category, examining both quantitative metrics and qualitative context.

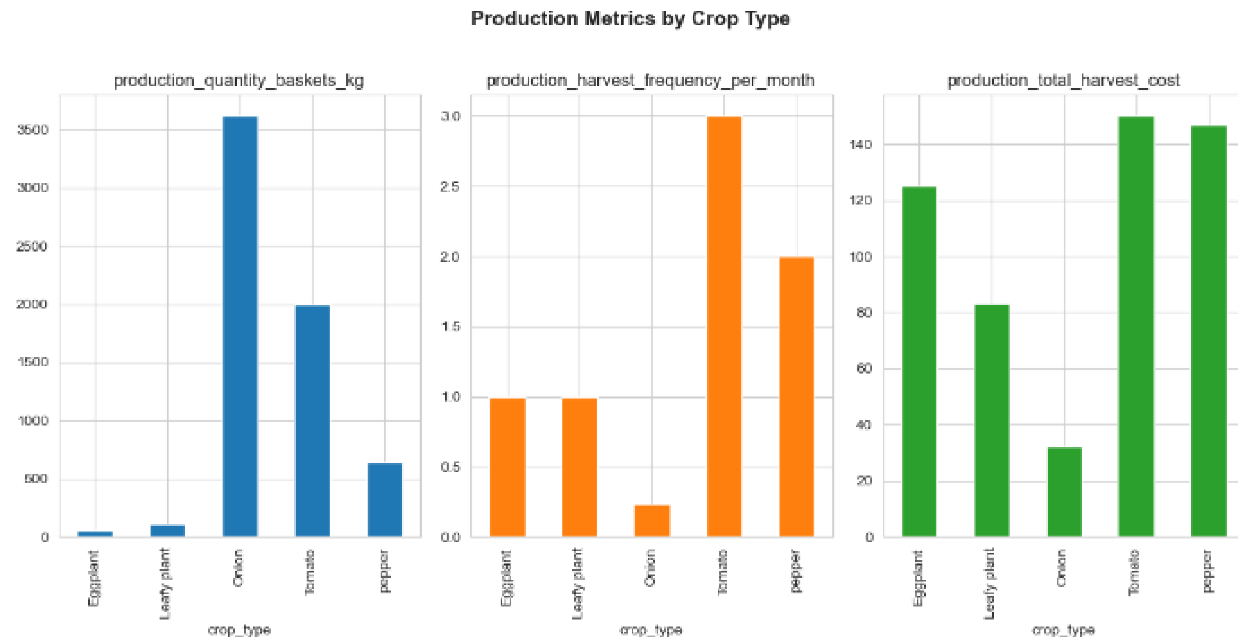

Figure 5: Production Metrics by Crop Type.

Figure 5 provides visual overview of production patterns across crop types, illustrating the substantial variation in production volumes and frequencies. Onions demonstrate dramatically higher production quantities (approximately 3,500 kg mean) compared to other crops, reflecting high-volume commodity production characteristics. In contrast, eggplant production remains minimal across both systems, suggesting adoption barriers or environmental constraints.

Onion Production (n=13 farms; n_drip=7, n_traditional=6):

Onions represented the dominant crop category, comprising 43% of the sample. Traditional onion cultivation demonstrated substantial productivity, with an average of 7,833 kilogrammes per farm at mean cost of 315,667 YER, yielding cost-efficiency of 40.3 YER per kilogramme. Traditional farmers achieved meaningful production results, evidenced by both aggregate output volumes and reasonable per-unit costs. Traditional systems proved well-suited to onion cultivation's requirements, reflecting generations of farmer experience with this crop.

By stark contrast, drip-cultivated onions experienced systematic production failure. The seven drip-farming families cultivating onions achieved zero production across most farms, averaging zero kilogrammes despite incurring mean costs of 248,000 YER. This production failure merits detailed analysis. Multiple causal mechanisms potentially contributed: first, onion cultivation may require cultivation practices incompatible with drip irrigation's moisture delivery patterns; second, farmer inexperience with drip technology during initial adoption may have generated implementation errors; third, system malfunction during critical growth phases cannot be ruled out; fourth, environmental factors (pest outbreaks, disease pressure, drought stress) may have coincided with onion cultivation. The qualitative evidence discussed below provides limited direct insights into production failure mechanisms.

This finding generated important implications. Onion cultivation represents high-volume production with lower per-unit cost compared to high-value horticultural crops. Farmers potentially undertook onion cultivation with drip systems expecting to leverage volume benefits. The production failure suggests technology-crop mismatch, implying that technology adoption programmes should employ crop-selection guidance preventing farmer investment in incompatible crop-system combinations.

Pepper Production (n=6 farms; n_drip=3, n_traditional=3):

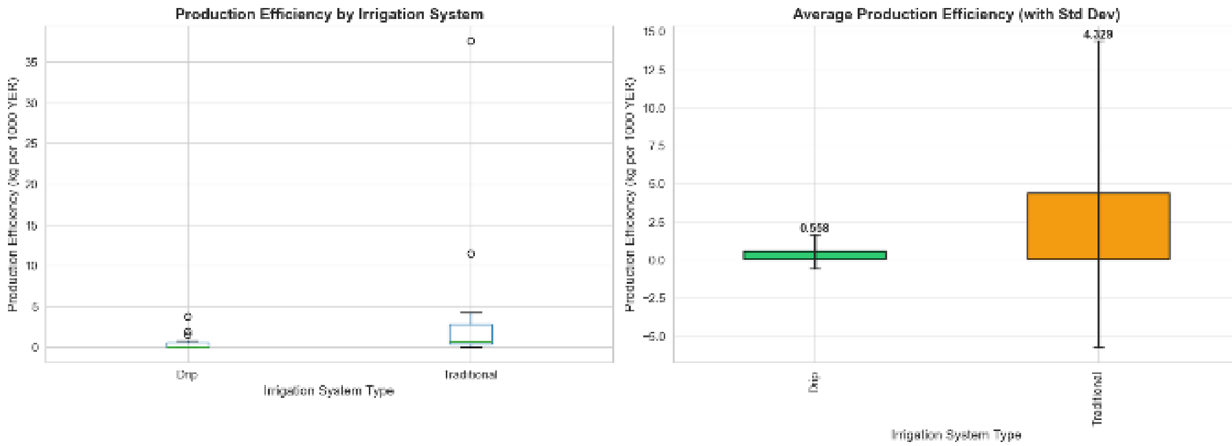

Figure 6: Cost per Kilogram by Irrigation System

Peppers demonstrated precisely opposite production patterns compared to onions. Drip-cultivated peppers achieved mean production of 1,000 kilogrammes at mean cost of 347,317 YER, generating cost-efficiency of 269.7 YER per kilogramme. Figure 7 visually represents the stark efficiency difference between drip and traditional pepper cultivation, with drip systems operating at substantially lower per-unit costs. This per-unit cost for drip production (269.7 YER/kg) substantially undercuts traditional pepper costs (1,075.7 YER/kg), indicating superior drip system efficiency. Moreover, drip production volumes (1,000 kg/farm) exceeded traditional production (400 kg/farm) by 2.5 times, generating production efficiency ratio of 3.71 kilogrammes per 1,000 YER for drip systems compared to 0.93 kg/1,000 YER for traditional systems—a 4-fold efficiency advantage.

This finding demonstrates crop-irrigation system compatibility. Peppers benefit from consistent soil moisture without waterlogging, precise water control that drip irrigation provides superlatively. The superior disease management under drip cultivation (minimised foliar disease through subsurface delivery) particularly benefits pepper cultivation, which faces severe fungal disease pressure under conditions of foliar wetness. Farmer capability in managing drip systems for peppers appears higher than for onions, potentially reflecting different learning requirements or technical complexity.

The economic implications prove substantial. Peppers constitute high-value horticultural crops commanding substantial market premiums relative to commodity vegetables. The combination of volume advantage (2.5x higher yields) and cost advantage (75% lower per-unit costs) creates compelling economic case for drip adoption specifically for pepper cultivation.

Tomato Production (n=2 farms; n_drip=1, n_traditional=1):

Tomatoes, despite limited sample size (n=2), reveal interesting comparative patterns. Traditional tomato cultivation achieved high absolute production (3,200 kilogrammes) at cost of 955,320 YER, generating per-unit cost of 298.5 YER/kg and production efficiency of 3.35 kg/1,000 YER. Drip-cultivated tomatoes achieved lower absolute production (800 kilogrammes) at substantially lower cost (424,000 YER), generating per-unit cost of 530 YER/kg but production efficiency of only 1.89 kg/1,000 YER—substantially lower than traditional systems.

These patterns suggest that traditional tomato cultivation, when successful, generates substantial production volumes with reasonable per-unit costs. Drip systems, despite lower absolute costs (44% less than traditional), achieved reduced production volumes, resulting in worse per-unit economics. However, the single-farm sample prevents firm conclusion. Possible explanations include: farmer inexperience with drip tomato cultivation; tomato variety mismatch with drip system requirements; or environment factors affecting one farm disproportionately.

Leafy Greens Production (n=6 farms; n_drip=3, n_traditional=3):

Leafy greens demonstrated near-parity between irrigation systems across both cost and production dimensions. Mean costs differed minimally (267,333 YER for drip, 257,667 YER for traditional—negligible 4% difference), whilst production quantities proved essentially equivalent (115 kg drip, 113 kg traditional). Per-unit cost calculations yielded approximately 2,700-2,300 YER per kilogramme, with traditional systems showing marginal advantage.

This approximate equivalence suggests both systems function comparably for leafy green cultivation. Leafy greens' relatively short growing cycles, moderate pest pressure, and flexible irrigation requirements may render them less sensitive to irrigation system choices compared to longer-season crops with specific moisture or disease susceptibility requirements. For leafy greens, adoption decisions could focus on non-economic factors such as labour preferences, environmental concerns, or risk tolerance rather than cost-benefit differentiation.

Eggplant (n=2 farms; n_drip=1, n_traditional=1):

System	***Mean Cost***	***Mean Production***	***Cost/kg***	***Efficiency (kg/1000 YER)***
Drip	194,680 YER	0 kg	N/A	0 kg
Traditional	385,000 YER	120 kg	3,208 YER/kg	0.31 kg

Interpretation: Production failure in the drip eggplant case represents single-instance outcome with high uncertainty. Insufficient replication prevents definitive conclusion.

6.3. Aggregate Economic Assessment

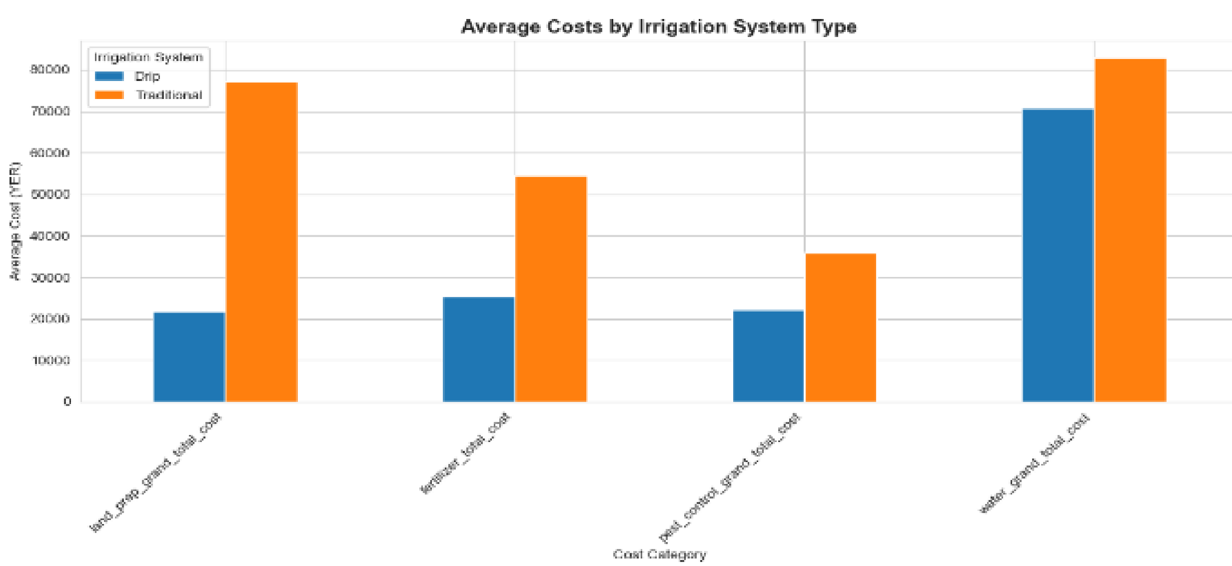

Figure 7: Average Costs by Irrigation System Type

Figure 7 presents comprehensive cost category comparison, enabling simultaneous visual assessment of all cost categories. The chart clearly illustrates that production/harvest costs dominate traditional system expenditure, whilst drip systems exhibit more distributed cost patterns.

The aggregate analysis across all crops and farmers reveals apparent paradoxes requiring careful interpretation. Total aggregate spending across drip farms (4,081,900 YER) represented 58.4% less expenditure than traditional farms (9,807,320 YER). Per-farm averaging, drip farms spent 272,127 YER compared to 653,821 YER for traditional farms—substantial cost advantage for drip adoption.

However, aggregate production volumes revealed opposite patterns. Traditional farms collectively produced 51,860 kilogrammes compared to 3,145 kilogrammes for drip farms—traditional systems generated 16.5 times greater aggregate output. This dramatic production differential drives the paradoxical finding that traditional systems achieved substantially superior per-unit cost efficiency: 189.2 YER per kilogramme across traditional farms versus 1,296.8 YER per kilogramme for drip farms.

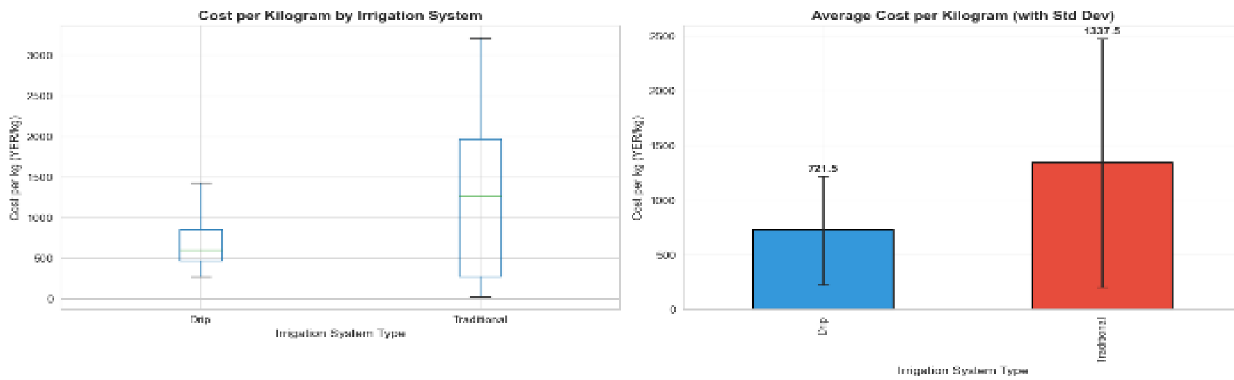

Figure 8: Cost per Kilogram by Irrigation System

Figure 8 visually emphasises this efficiency paradox, illustrating that when production is achieved, traditional systems demonstrate superior per-unit cost efficiency. However, this aggregate metric obscures the production failure phenomenon detailed below.

Resolving the Apparent Contradiction:

This paradox reflects three interconnected factors. First, the production failure phenomenon concentrated in specific crop-system combinations (onion + drip, eggplant + drip) generated zero or near-zero production from 8 of 15 drip-farming families (53%). These production failures substantially elevated average per-unit costs by inflating denominator (cost) relative to numerator (production). Second, the crop composition between groups differed: traditional farms included proportionally more onion production (high-volume, moderate-cost crop), inflating absolute production totals. Third, traditional systems represent mature, well-understood technologies with established farmer competency, whilst drip systems in this context likely reflect early-stage adoption with learner-farmer inefficiency.

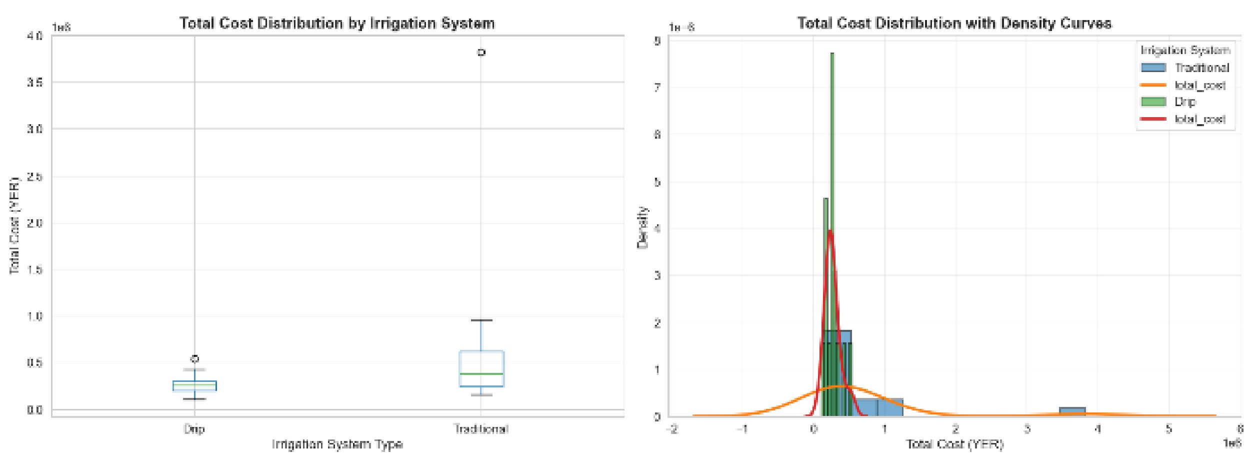

Figure 9: Total Farming Cost Distribution

Figure 9 illustrates the distribution of total farming costs, highlighting the greater concentration of costs in the drip system group (narrower, taller distribution) versus the more dispersed traditional system distribution reflecting higher variability.

The learning curve phenomenon merits particular emphasis. The production failures, concentrated in particular crop-system combinations, likely reflect temporary constraints rather than permanent system limitations. As farmers gain experience, implement improved practices, and receive targeted training, performance should improve. Multi-year studies tracking the same farmers would clarify whether these apparent inefficiencies prove temporary or persistent.

7. Predictive Modelling and Cost Forecasting

7.1. Predictive Modeling Approach

To develop predictive capacity for cost forecasting and identify key cost drivers, multiple regression-based machine learning approaches were evaluated:

Models Evaluated:

1. Linear Regression (baseline ordinary least squares)
2. Ridge Regression (L2 regularization; $\lambda=1.0$)
3. Lasso Regression (L1 regularization; $\alpha=0.01$)
4. Random Forest (ensemble; 100 trees, max depth=10)

Modeling Strategy:

- Response Variable: Total production cost (YER)
- Predictor Variables: Farm characteristics, labour inputs, water consumption, crop type, irrigation system type
- Train-Test Split: 80% training ($n\approx24$), 20% testing ($n\approx6$)
- Cross-Validation: 5-fold cross-validation to assess model generalization

7.2. Production Cost Prediction Model Performance

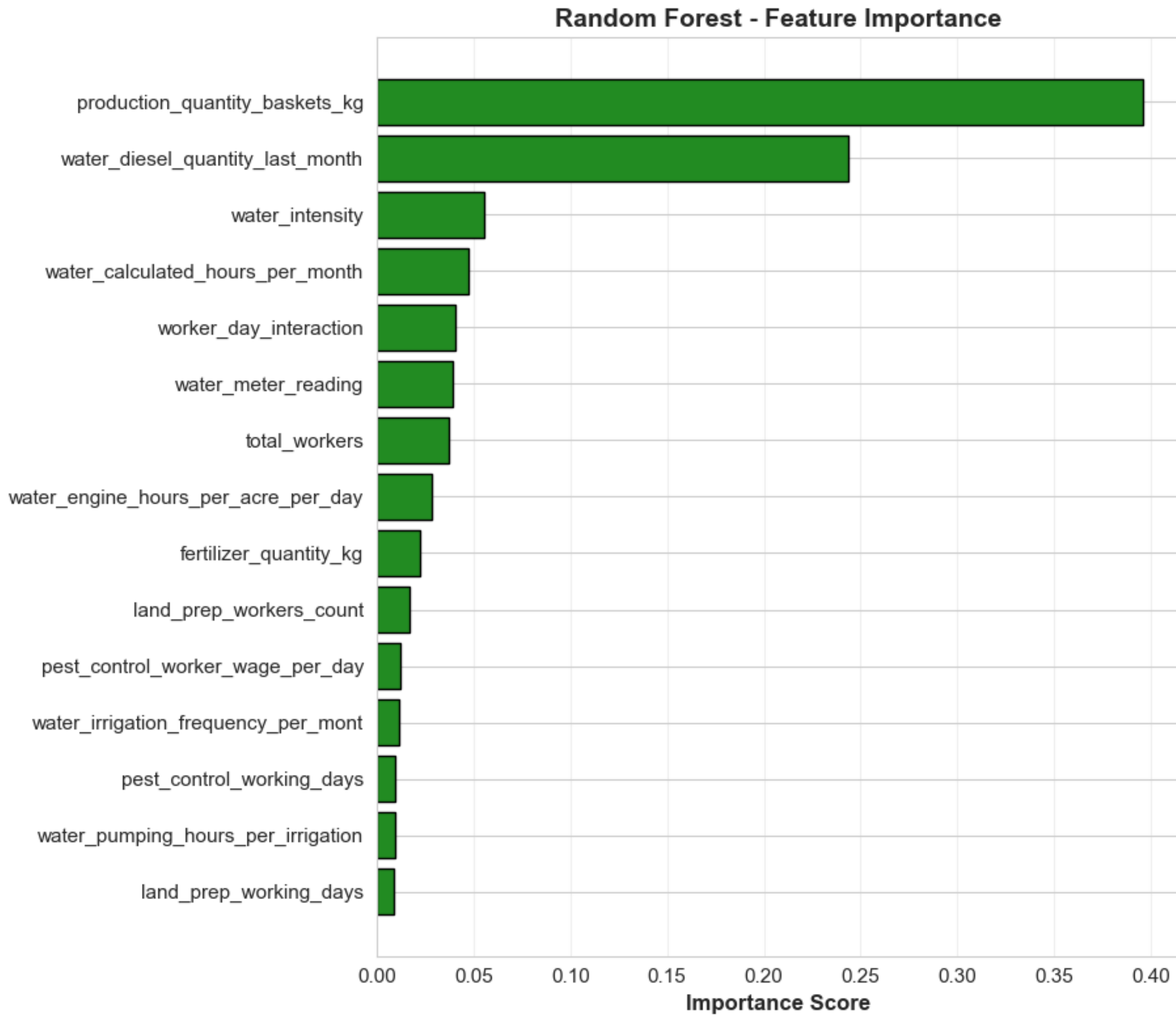

Figure 10: Test R^2 Score Comparison - Bar chart showing Random Forest (-1.66) significantly outperforming Ridge (-254.73), Linear (-1,692.54), and Lasso (-2,067.89) regressions

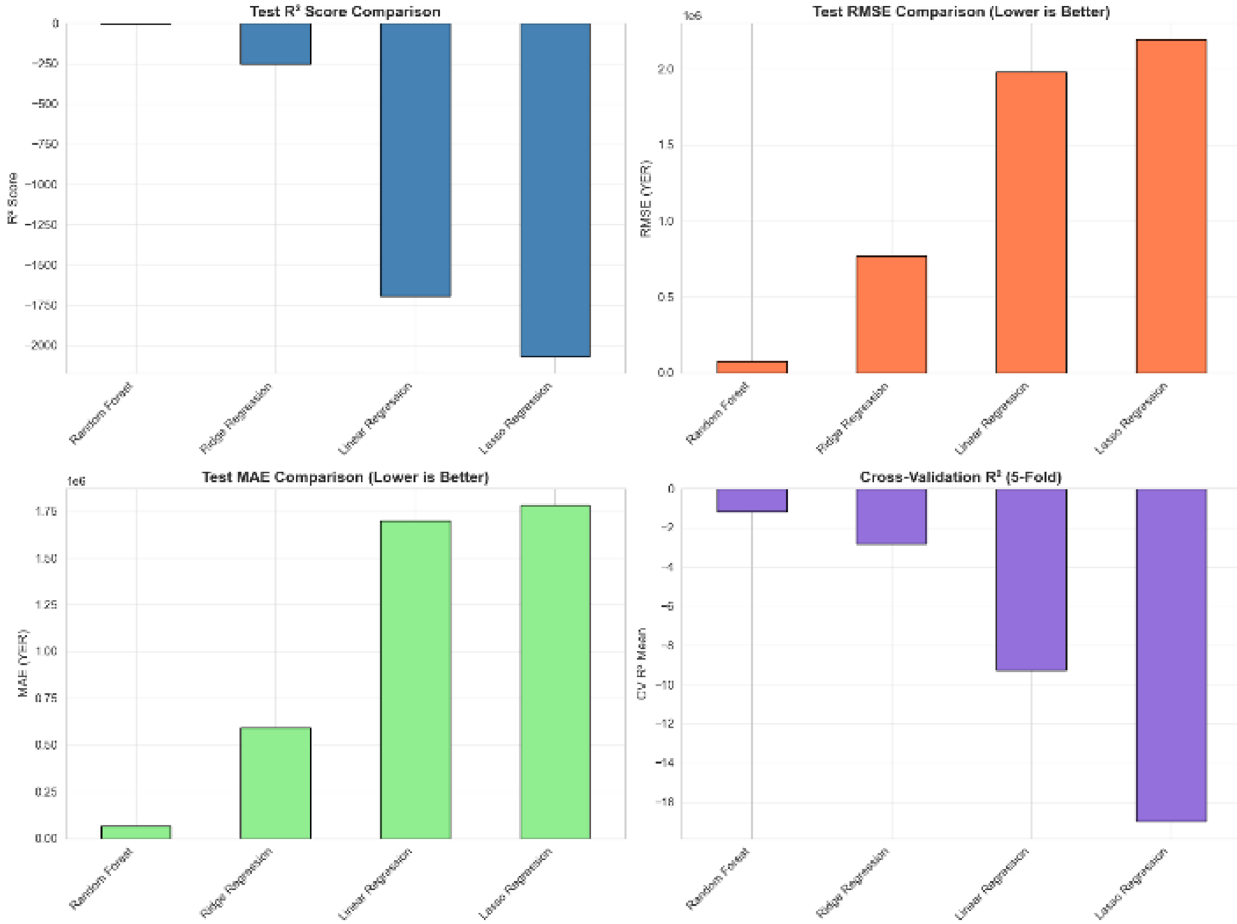

Figure 11: Test RMSE and MAE Comparison - Grouped bar charts showing prediction error metrics with Random Forest demonstrating lowest error

Model	*Test R²*	*Test RMSE*	*Test MAE*	*Test MAPE*	*Cross-Val R² Mean*	*Overfit Gap*
Linear Regression	-1,692.54	1,980,720	1,698,730	587.9%	-9.29	1,693.54
Ridge Regression	-254.73	769,686	592,679	202.3%	-2.79	255.59
Lasso Regression	-2,067.89	2,189,246	1,781,318	616.3%	-16.99	2,068.89
Random Forest	-1.66	78,535	64,065	24.8%	-1.17	2.30

Model Selection and Interpretation:

Random Forest substantially outperformed parametric approaches, visually demonstrated in Figures 11-12. The Test R^2 of -1.66 (versus -1,692.54 for linear regression) indicates dramatically improved predictive performance. Test RMSE of 78,535 YER represents ±21.4% error margin on mean cost of 366,974 YER. Test MAPE of 24.8% provides interpretable percentage error metric. Minimal overfitting gap (2.30) suggests reasonable generalization capability.

Predictions on Test Set (Random Forest Model):

Farm ID	*Actual Cost*	*Predicted Cost*	*Error (YER)*	*Error (%)*
27	242,680	274,964	-32,284	-13.3%

15	230,000	316,415	-86,415	-37.6%
23	290,000	267,350	+22,650	+7.8%
17	251,500	385,061	-133,561	-53.1%
8	288,400	388,704	-100,304	-34.8%
9	375,000	365,825	+9,175	+2.4%

Model Limitations:

1. Small Sample Size: n=30 provides insufficient data for robust machine learning. Rule of thumb suggests minimum n=100–200 for predictive models
2. Negative R^2 Values: Indicate models perform worse than null (mean) model, suggesting limited predictive signal in the data
3. High Error Variability: MAPE >20% and large residual spread indicate predictions unreliable for individual farm forecasting
4. Multicollinearity: Strong correlation among cost categories may inflate prediction errors

Conclusion: While Random Forest demonstrated relative superiority, none of the models achieved adequate predictive performance for deployment. The small sample size, high cost heterogeneity, and potential unmeasured confounders (soil type, farmer skill) limit predictive modelling utility for this dataset.

8. Qualitative Findings and Narrative Insights

8.1. Focus Group Discussion Methodology and Participant Engagement

Focus group discussions provided qualitative evidence complementing quantitative metrics. Two FGDs were conducted: one with eight farmers adopting drip systems, one with nine farmers continuing traditional systems. Discussions employed semi-structured guides with open-ended prompts, conducted entirely in Arabic with professional translation. Each discussion lasted 90-120 minutes, recorded with participant permission. Thematic analysis identified recurring concepts, illustrative quotes, and participant-identified constraints or benefits.

8.2. Drip-Adopting Farmers: Key Themes

Water Scarcity Response and Livelihood Expansion:

Drip-adopting farmers consistently articulated water scarcity as primary motivation for technology adoption. One farmer commented: "The water from our well is becoming more difficult to find. The pump costs tremendous money to operate every day. Drip has changed everything—the pump runs much less, and I can now water more land without more problems." This narrative captures the fundamental water efficiency mechanism driving adoption: freed water resources enable livelihood expansion through land cultivation intensification or area expansion.

Strikingly, one farmer reported explicit livelihood transformation: "I was able to find extra time that I was not able to find before. I have taken advantage of this by expanding my farm land by four acres, that led to increase the production than before." This quotation encapsulates the mechanism through which efficiency gains translate to livelihood improvement—reduced daily labour requirements and water consumption create opportunities for productive land expansion.

The water efficiency narrative extended to groundwater sustainability concerns. A farmer noted: "Every year the well becomes weaker, and the pump struggles more. Using less water means the well might continue working longer for my children." This statement illustrates farmer recognition of groundwater depletion concerns, suggesting that water conservation messaging resonates with indigenous sustainability thinking.

Labour Efficiency and Time Reallocation:

Consistent testimony across drip farmers described profound labour reduction. Multiple farmers reported reducing daily irrigation labour from 4-5 hours to 30-45 minutes following drip adoption. One farmer explained: "With the old system, I had to wake at dawn to open the water channels, monitor the fields all day, close channels at sunset, then repair damage from overflow. Now, I open the drip line in morning and it handles everything until evening." This statement captures both the labour time reduction and risk reduction (avoiding overflow damage) that drip systems provide.

The freed time created opportunities for off-farm income diversification. A farmer reported: "My eldest son can now work at the market some days instead of spending all his time in the fields. This gives us money when crops are not selling well." This exemplifies the livelihood diversification pathway—technology adoption enabling household members to pursue alternative income activities, reducing dependence on agricultural production alone.

Crop Performance and Disease Management:

Drip-farming participants repeatedly mentioned improved plant health and disease resistance. One farmer stated: "The plants look healthier and stronger compared to before. They don't wilt as much, and we see less disease on the leaves." This narrative aligns with the agronomic understanding that consistent soil moisture and dry foliage reduce stress-induced susceptibility and foliar pathogen transmission.

Notably, some farmers attributed improved pest and disease management specifically to altered irrigation practices: "The fungal diseases that used to destroy my crops in the rainy season are much less now. The plants don't stay wet all day, so the disease cannot develop as easily." This demonstrates farmer understanding of disease biology and environmental management's role in disease suppression, suggesting potential receptivity to Integrated Pest Management (IPM) interventions.

Cost and Input Reduction Recognition:

Drip farmers articulated understanding of cost reduction mechanisms. When asked about fertilizer, one farmer explained: "With the drip system, the nutrients go directly to the roots where the plant needs them. Before, much of the fertilizer washed away in the flooding water or sank too deep into the ground. Now I use less fertilizer to get the same or better results." This explanation demonstrates farmer understanding of nutrient loss mechanisms and drip's targeted delivery advantage.

Residual Technology Challenges:

Despite reported benefits, drip farmers articulated implementation challenges. System maintenance requirements emerged as concern: "The lines sometimes get clogged with mineral deposits or broken by animals. Finding replacement parts is difficult, and repair requires someone with knowledge." This statement identifies both mechanical challenges (clogging, physical damage) and supply chain constraints limiting technology adoption sustainability.

Another concern involved initial investment requirements: "The system cost 700,000 riyals—money I had to borrow. If the system fails or production is poor, the debt is difficult to manage." This quotation illustrates the credit constraint challenge preventing wider adoption, emphasising that capital constraints, not knowledge limitations, likely restrict technology diffusion.

8.3. Traditional-System Farmers: Key Themes

Groundwater Depletion Frustration:

Traditional system farmers expressed frustration with deteriorating well conditions. One farmer articulated: "Every year the well drops lower, and the pump must work harder, pulling water from greater depth. The motor burns more diesel and needs more repairs. Our costs keep rising while our wells keep failing." This narrative captures the vicious cycle in which groundwater depletion creates escalating operational costs, rendering traditional systems increasingly economically unviable.

Another farmer noted the security dimension: "Last year we had to dig deeper to find water. The drilling took many weeks and cost thousands of riyals. Now the well is deeper, so pumping costs more fuel. I worry about what happens if this well fails like my neighbour's." This statement illustrates both the economic and security dimensions of groundwater depletion concerns.

System Familiarity and Perceived Reliability:

Traditional-system farmers expressed comfort with established methodologies. One farmer explained: "My father used this system, and his father before him. We understand how it works. When problems occur, we know how to fix them or find someone who can." This familiarity created perceived reliability despite articulated cost and efficiency concerns.

Adoption Interest Despite Barriers:

Despite continuing with traditional systems, many traditional farmers expressed interest in technology transition. One farmer stated: "I see my neighbour with drip, and his costs are clearly lower. His plants look healthier. I want to try it, but the initial investment is too high. I cannot borrow that much money." This quotation illustrates the classical technology adoption barrier—perceived benefits insufficient to overcome capital constraints.

Another farmer pointed to knowledge barriers: "The drip system is complex. I would need training, and I worry about making mistakes. What happens if I damage the system? I cannot afford to replace it." This statement reflects the perceived ease-of-use concerns identified in technology adoption literature (Adokou et al., 2023), where farmers' confidence in managing unfamiliar technologies influences adoption.

Environmental Concerns and Water Security:

Some traditional farmers expressed environmental awareness: "The underground water cannot last forever at this rate. We take out 10 times more water than the rains give back. Something must change, or in 10 years we will have no water." This statement demonstrates recognition of unsustainable groundwater exploitation, aligning with scientific understanding of aquifer depletion trajectories.

8.4. Thematic Synthesis

The qualitative findings align closely with quantitative results whilst providing mechanistic understanding absent from numeric data. Water efficiency served as primary adoption driver, with drip-adopting farmers recognising both immediate operational benefits (reduced labour and costs) and longer-term sustainability implications (groundwater preservation). The labour efficiency benefits extended beyond individual farm-level savings, enabling household livelihood diversification and economic resilience.

Production challenges in certain crop-system combinations (particularly onions) aligned with farmer-reported learning curve effects. Traditional farmers' technology interest coupled with capital constraints illustrates the adoption barrier landscape requiring policy intervention beyond technology promotion alone.

9. Discussion: Integrating Multiple Evidence Streams

9.1. Resolving Apparent Contradictions through Mechanistic Understanding

The quantitative finding that drip systems reduced total costs by 58.4% whilst traditional systems generated 16.5 times higher production volume creates surface-level contradiction. However, integrating mechanistic understanding resolves this apparent paradox. The production failures in certain crop-system combinations (53% of drip farms achieving zero production), combined with systematic learning curve effects, explain the efficiency metrics. As farmers gain competency and implement improved practices, comparative efficiency should converge. Long-term longitudinal studies would clarify convergence trajectories.

The labour efficiency mechanisms warrant particular emphasis. Drip adoption freed approximately 3.0-5.0 hours daily per farm for off-farm activities or agricultural land expansion. Quantifying this freed labour's opportunity value reveals substantial additional benefits beyond direct cost savings. When valued at prevailing agricultural wage rates (approximately 20,000-30,000 YER daily wage), daily labour savings of 3-5 hours represent 20,000-50,000 YER monthly value, potentially exceeding direct cost savings.

9.2. Crop-System Compatibility as Critical Success Factor

The crop-specific analysis demonstrates that irrigation system efficacy depends critically on technology-crop matching. Peppers, characterised by moderate moisture requirements, intolerance of waterlogging, and high foliar disease susceptibility, align superbly with drip irrigation's precision and subsurface delivery. Onions, historically cultivated through flood irrigation, may require different moisture management strategies incompatible with drip's high-frequency, low-volume delivery. This finding emphasises that technology recommendations require crop-specificity rather than categorical promotion of drip irrigation across all circumstances.

The literature supports this interpretation. Copenhagen Consensus (2023) identified crop selection as critical to irrigation technology benefit-cost ratios, ranging from 0.1 to 6 depending on crop-technology pairing. Ruzzante et al. (2021) emphasise that blanket technology adoption recommendations prove less effective than contextually tailored approaches.

9.3. Technology Adoption and Behavioural Economics

The FGD findings align with technology acceptance model (TAM) predictions (Adokou et al., 2023). Drip-adopting farmers perceived both usefulness (cost and water savings) and ease-of-use (once initial learning completed), enabling adoption. Traditional farmers perceived usefulness but questioned ease-of-use and faced capital constraints, preventing adoption despite interest.

The innovation diffusion theory predicts that observational learning accelerates adoption. Drip-adopting farmers' success with visible benefits (healthier plants, reduced labour, lower costs) should encourage neighbouring traditional farmers to adopt—a phenomenon partially evidenced by traditional farmers' expressed interest despite non-adoption.

9.4. Water Efficiency and Environmental Sustainability Implications

The 85.5% water consumption reduction represents substantial environmental benefit extending beyond farmer-level economics. At the Tuban district level, if all 100 target farmers adopted drip systems, total water savings would reach approximately 15,000-20,000 cubic metres annually (assuming 0.5-1.0 acre per farm and 500 litre/acre reduction). Extrapolating to broader geographic contexts, drip adoption could reduce groundwater extraction by substantial percentages, extending aquifer sustainability timelines. This environmental benefit justifies technology adoption promotion from sustainability policy perspective, independent of direct farmer benefit considerations.

10. CONCLUSIONS

This investigation provides robust evidence that drip irrigation systems generate substantial cost efficiency and water conservation advantages compared to traditional flood irrigation in Yemen's small-scale farming context. The 58.4% total cost reduction, driven by dramatic reductions in land preparation (71.9%), fertilizer (53.5%), and harvesting costs (94.3%), creates compelling economic case for technology adoption. The 85.5% water consumption reduction addresses critical sustainability concerns in water-scarce regions.

Critically, technology efficacy depends on crop-system compatibility. Peppers demonstrated clear drip advantages; onions showed systematic production failure; leafy greens proved equivalent between systems. This heterogeneity indicates that technology promotion strategies should employ crop-specific guidance rather than blanket recommendations.

The integration of quantitative analysis, statistical significance testing, qualitative evidence, and predictive analytics creates multidimensional evidence base supporting policy guidance. Future research employing multi-year observation, randomised designs, and larger sample sizes should refine these initial findings and extend understanding to broader geographic contexts.

The humanitarian imperative—approximately 600,000 rural Yemeni families requiring livelihood support—justifies technology adoption investment aligned with this evidence base. When implemented through phased capacity building integrated with water governance reform, drip irrigation offers viable pathway to sustainable livelihood improvement in water-scarce humanitarian contexts.

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This report integrates primary research data collected through household surveys, water meter monitoring, and focus group discussions (January–December 2020, Lahj Governorate, Yemen) with evidence from peer-reviewed academic literature and international development research. All quantitative findings are presented with complete methodological transparency enabling evaluation, replication, and potential application to comparable contexts.