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RESOURCE USE EFFICIENCY IN COTTON CULTIVATION IN PUNJAB, PAKISTAN: IMPLICATIONS FOR SUSTAINABLE PRODUCTION AND AGRICULTURAL EXTENSION

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ABSTRACT

Cotton is a strategically important crop in Pakistan because it supplies raw material to the textile industry and supports rural livelihoods. Improving cotton productivity and profitability requires efficient allocation of land, seed, fertilizer, irrigation water, and crop-protection resources. This study examines resource-use efficiency among 535 cotton growers in Bahawalpur, Bahawalnagar, Rahim Yar Khan, and Khanewal districts of Punjab, Pakistan. Primary data were collected during the 2021 growing season through a multistage sampling procedure. A log-linear Cobb–Douglas production function was used to examine the relationship between cotton yield and selected farm, farmer, and input variables. Marginal value product (MVP) to marginal factor cost (MFC) ratios were used to assess the economic use of selected inputs. The estimated model explains 33.5% of the variation in cotton yield (R^2 = 0.335). Farm size, cotton area, number of ploughings, and seed use show statistically significant associations with yield, while the coefficients for farmer age, farming experience, laser land levelling, urea, DAP, canal irrigation, and pesticide sprays are not statistically significant. The MVP/MFC ratios indicate that ploughing, urea, canal irrigation, and pesticide sprays have ratios below unity, whereas laser land levelling, seed, and DAP have ratios above unity. These findings highlight opportunities to improve farm performance through better input allocation, soil and water management, and integrated pest management. Agricultural extension services can support these improvements through practical, locally adapted advice and field-based demonstrations.

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is an important fibre crop and a major source of raw material for Pakistan's textile and associated industries. Its economic importance extends beyond the farm because cotton production supports ginning, spinning, weaving, edible-oil processing, livestock feed, transport, and rural employment. Cotton picking also provides seasonal employment, particularly for rural women. Consequently, the performance of cotton farms has implications for household livelihoods, industrial supply chains, and export earnings (Government of Pakistan, 2020; Nadeem et al., 2014).

The sustainability of cotton production depends not only on the quantity of inputs applied but also on the efficiency with which land, seed, fertilizer, water, labour, and plant-protection resources are combined. Excessive or poorly timed applications may increase production costs without generating a proportionate yield response. Inappropriate pesticide use can also create risks for farm workers, beneficial organisms, environmental quality, and public

health (Tariq et al., 2007; Mancini et al., 2005; Ullah and Perret, 2014).

Research on cotton production in Punjab has repeatedly identified technical, allocative, and environmental inefficiencies. Shafiq and Rehman (2000) documented considerable resource-use inefficiency among cotton farms in the cotton–wheat system of Punjab. Later work on irrigated cotton-cropping systems found that farms could reduce environmental impacts through improved input combinations, while extension exposure and training were positively associated with efficiency (Ullah and Perret, 2014). Research on water management also indicates that substantial opportunities may exist to improve cotton output through more efficient irrigation and farm-level water decisions (Watto and Mugera, 2015). More recent evidence from Pakistan emphasizes that sustainable cotton production is associated with the adoption of improved agronomic and climate-adaptation practices. Comparing sustainable and conventional cotton producers, Mehmood et al. (2024) found higher average yields and profitability among sustainable cotton producers in their sample, alongside differences in the use of seed, irrigation, fertilizer, pesticide, and harvesting practices. International evidence also indicates that cotton water-use and nitrogen-use efficiencies can be improved through better coordination of irrigation and nitrogen inputs (Wang et al., 2024).

Agricultural extension has a central role in translating such evidence into farm practice. Farmers need practical guidance on soil preparation, seed rate, fertilizer selection and timing, irrigation scheduling, pest scouting, and the economic consequences of additional input applications. Evidence from Punjab indicates that extension and training are relevant to technical and environmental efficiency in cotton production (Ullah and Perret, 2014), while studies of cotton integrated pest management have highlighted the importance of extension field staff in communicating crop-protection practices to growers (Adeel et al., 2023).

METHODOLOGY

Study area

The study was conducted in four cotton-producing districts of Punjab, Pakistan: Bahawalpur, Bahawalnagar, Rahim Yar Khan, and Khanewal. These districts were selected because of their importance in cotton cultivation in the province. Figure 1 in the original manuscript presents the geographical location of the selected districts.

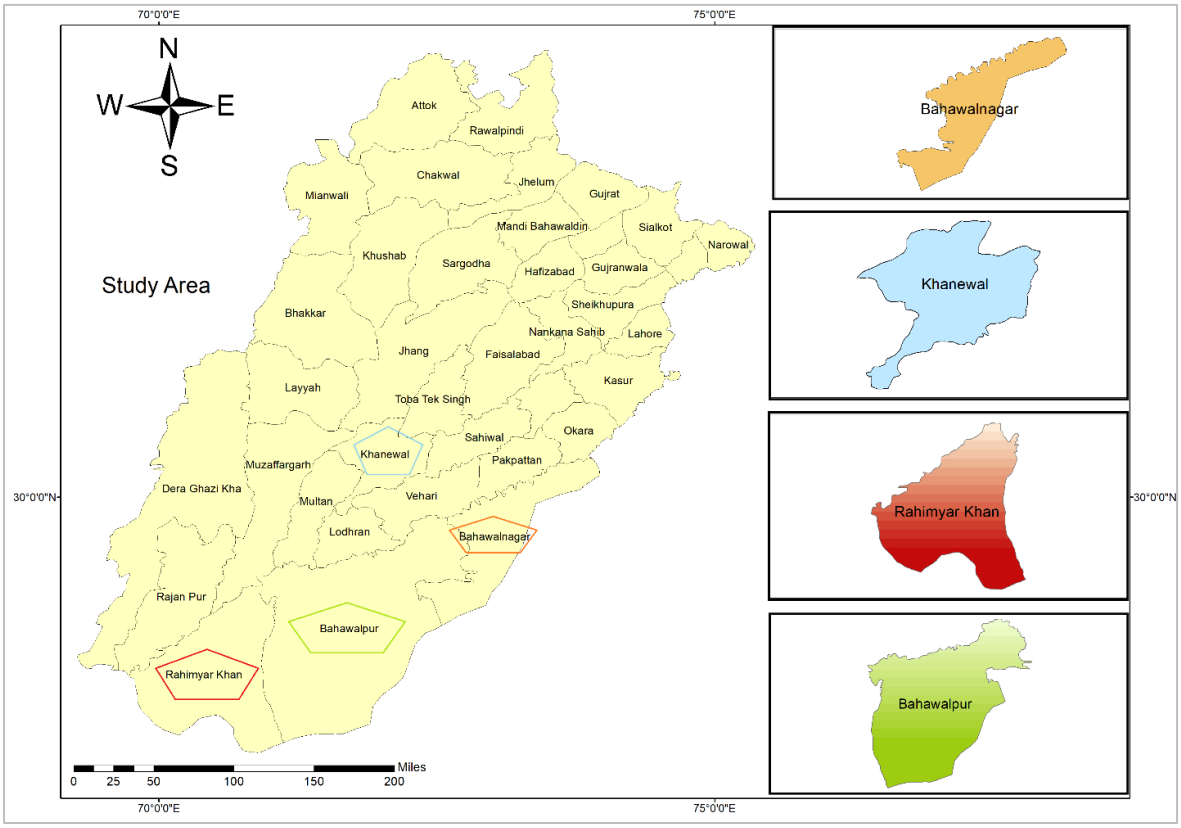


Figure 1. Study area map.

Sampling procedure and data collection

A multistage sampling procedure was used to select 535 cotton growers. The four districts were selected purposively because of their importance in cotton production. Villages within the selected districts and respondents within those villages were then selected randomly. The sample comprised 165 growers from Bahawalpur, 135 from Bahawalnagar, 125 from Rahim Yar Khan, and 110 from Khanewal. The manuscript refers to the sample-size formula attributed to Yamane (1967), using a stated precision level of 10% (Figure 2). Primary data were collected through a structured and pre-tested questionnaire during the 2021 growing season. The questionnaire was reviewed in consultation with cotton specialists, research institutions, and extension workers. Four enumerators with master's-level training in agricultural economics were engaged, one for each district, and received field and classroom training. Face-to-face interviews were conducted with the selected growers.

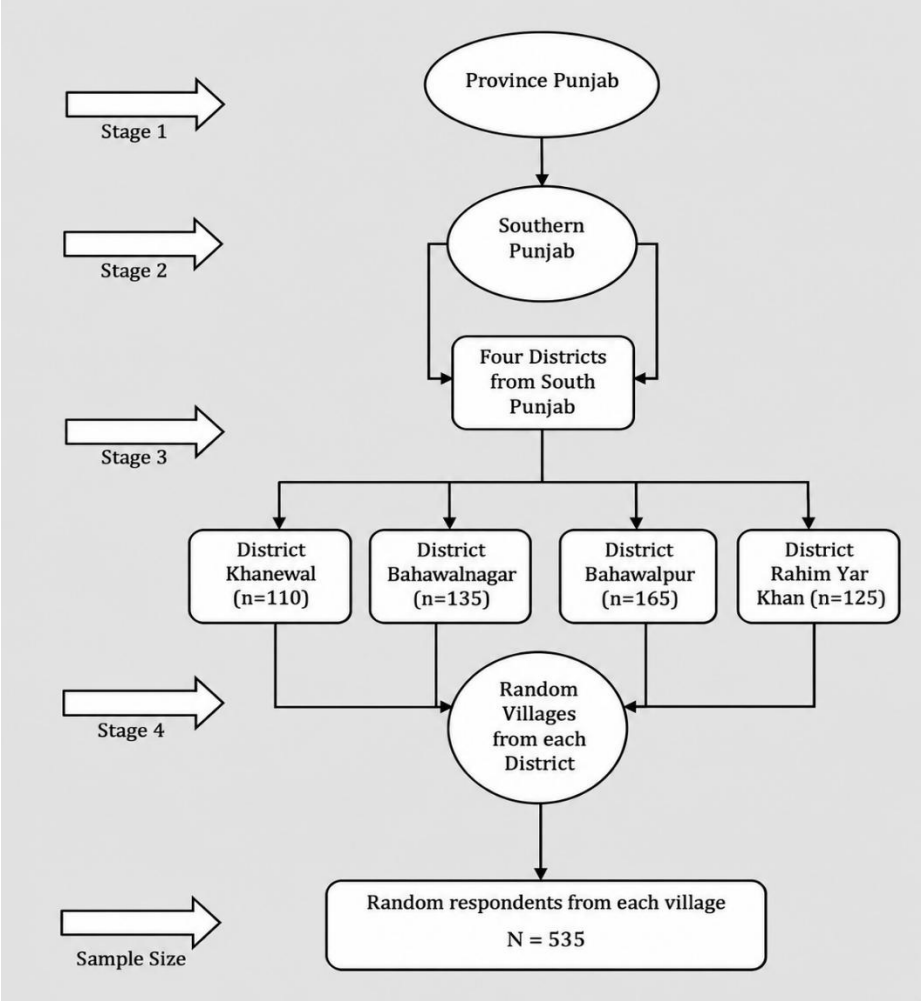


Figure 2. sampling framework.

Analytical framework

The study employed a Cobb–Douglas production function to estimate the relationship between cotton yield and selected socioeconomic and production variables. The Cobb–Douglas form is widely used in agricultural production analysis because its log-linear specification provides coefficients that can be interpreted as output elasticities when the dependent variable and continuous explanatory variables are expressed in natural logarithms (Ashfaq et al., 2012; Shafiq and Rehman, 2000).

The general production function is:

$Y_i = A \prod X_{ij}^{\beta_j} \exp(\mu_i)$

Taking natural logarithms gives:

$\ln Y_i = \beta_0 + \Sigma_j \beta_j \ln X_{ij} + \mu_i$

where Y_i is cotton yield for farm i; X_{ij} represents the jth explanatory variable; β_0 is the intercept; β_j is the estimated output elasticity; and μ_i is the random error term. The variables included in the original model are farmer age, cotton-growing experience, farm size, cotton area, number of ploughings, use of a laser land leveller, seed quantity, urea application, diammonium phosphate (DAP) application, canal irrigation, and pesticide sprays. The original table labels the variables as logarithmic.

Resource-use efficiency analysis

The economic efficiency of individual inputs was assessed by comparing the marginal value product (MVP) with the marginal factor cost (MFC). The ratio was calculated as:

$r_i = MVP_i / MFC_i$

For a Cobb–Douglas production function, the MVP of input i is calculated as:

$MVP_i = \beta_i \times (\bar{Y} / \bar{X}_i) \times P_Y$

where β_i is the estimated coefficient for input i, $\bar{Y}$ is mean output, $\bar{X}_i$ is mean use of input i, and P_Y is the output price. Following the decision rule adopted in the original study, r greater than one indicates underutilization, r less than one indicates overutilization, and r equal to one indicates economically efficient use of the input (Ashfaq et al., 2012). Negative MVP values require particular caution: they indicate a negative estimated marginal product at the sample mean and should not be interpreted as ordinary positive-return input ratios.

Statistical analysis

The OLS model is assessed using the coefficient of determination (R^2), t-statistics for individual coefficients. Statistical significance is evaluated at conventional 1%, 5%, and 10% levels. The economic efficiency of selected inputs is examined through MVP/MFC ratios, with values above unity indicating underutilization and values below unity indicating overutilization, subject to the sign and interpretation of the estimated marginal product.

RESULTS

Socioeconomic and farm characteristics

Table 1 presents the descriptive statistics of the 535 sampled cotton growers. The mean age of respondents was 47.39 years, while average farming experience and cotton-growing experience were 23.72 and 23.65 years, respectively. Mean formal education was 7.82 years, and average household size was 8.13 members. The mean total farm size was 21.98 acres, of which 20.91 acres were reported as operational landholding. The average area allocated to cotton was 16.68 acres, and mean cotton yield was 20.64 maunds per acre. The mean reported price of a urea bag was PKR 1,699, compared with PKR 3,563 for a DAP bag. Average tube-well irrigation cost was PKR 807 per acre, while the mean cost per pesticide spray was PKR 1,392. The reported picking cost was PKR 475 per maund, and total harvesting cost averaged PKR 9,846. The average selling price of cotton was PKR 5,044 per maund.

Table 1. Descriptive statistics of different variables.

Variable	Unit	N	Mean	Std. deviation
Age	Years	535	47.39	11.52
Farming experience	Years	535	23.72	12.44
Cotton-growing experience	Years	535	23.65	12.40
Education	Years	535	7.82	4.79
Total family members	Number	535	8.13	3.32
Total farm size	Acres	535	21.98	51.59
Operational landholding	Acres	535	20.91	48.99
Cotton area	Acres	535	16.68	40.78
Cotton yield	Maunds/acre	535	20.64	4.82
Urea price per bag	PKR	535	1,699	55.23
DAP price per bag	PKR	535	3,563	218.29
Tube-well irrigation rate	PKR/acre	535	807	240.76
Spray cost	PKR/spray	535	1,392	289.44
Picking cost	PKR/maund	535	475	44.00
Total harvesting cost	PKR	535	9,846	2,581.30
Cotton selling price	PKR/maund	535	5,044	589.95

Source: Field survey, 2021. Monetary values are reported in Pakistani rupees (PKR).

Cobb–Douglas production-function estimates

The estimated model has an R^2 of 0.335, indicating that the explanatory variables account for 33.5% of the variation in cotton yield. The coefficients for farmer age (0.032), cotton area (0.203), seed use (0.101), and DAP use (0.056) are positive, whereas farm size (−0.149), number of ploughings (−0.117), urea (−0.015), and canal irrigation (−0.012) have negative coefficients. The t-statistics, farm size, cotton area, number of ploughings, and seed use are statistically significant at conventional levels. The remaining coefficients are not statistically significant.

Table 2. Estimated Cobb-Douglas Production Function of cotton growers across different cotton growing area of Punjab, Pakistan.

Variable	Coefficient	t-value	Statistical inference
Constant	2.638	8.786	
ln(Age)	0.032	0.381	Not significant
ln(Cotton-growing experience)	0.023	0.676	Not significant
ln(Farm size)	−0.149	−3.654	Significant (p<0.01)
ln(Cotton area)	0.203	5.303	Significant (p<0.01)
ln(Number of ploughings)	−0.117	−2.035	Significant (p<0.05)
ln(Laser land leveller)	0.016	0.360	Not significant
ln(Seed use)	0.101	2.174	Significant (p<0.05)
ln(Urea bags)	−0.015	−0.359	Not significant
ln(DAP bags)	0.056	0.974	Not significant
ln(Canal irrigation)	−0.012	−0.326	Not significant
ln(Spray use)	0.015	0.198	Not significant
R^2	0.335	—	

Note: R^2 denotes the coefficient of determination. Statistical significance is assessed using the t-statistics.

Marginal value product and resource-use efficiency

Table 3 presents the reported marginal value product, marginal factor cost, MVP/MFC ratio, and input-use decision. The ratios classify ploughing (−7.49), urea (0.52), canal irrigation (−10.76), and pesticide sprays (0.19) as overutilized. Laser land levelling (1.82), seed use (4.46), and DAP application (1.50) are classified as underutilized.

Table 3. Resource use efficiency analysis of cotton growers.

Resource	MVP (PKR)	MFC (PKR)	MVP/MFC	Original decision
Ploughing (number)	−5,736	765	−7.49	Overutilized
Laser land levelling (hours)	1,463	800	1.82	Underutilized
Seed use (kg)	1,324	297	4.46	Underutilized
Urea (bag)	900	1,699	0.52	Overutilized
DAP (bag)	5,358	3,564	1.50	Underutilized
Canal irrigation (number)	−183	17	−10.76	Overutilized
Spray use (number)	269	1,392	0.19	Overutilized

The negative MVP estimates for ploughing and canal irrigation indicate that the fitted production function predicts a negative marginal contribution at the sample mean. Their negative ratios are therefore not simply low positive returns; they suggest that the estimated marginal product is negative within the fitted model.

DISCUSSION

The estimated model explains 33.5% of the observed variation in cotton yield (R^2 = 0.335), indicating that the included variables account for part, but not all, of the differences among sampled farms. Cross-sectional farm yields can also vary with soil fertility, seed variety, crop establishment, weather, pest pressure, irrigation timing, and management quality, several of which are not directly represented in the reported specification. Previous work on Punjab cotton has documented technical and allocative inefficiencies and emphasized the importance of farm-level input combinations (Shafiq and Rehman, 2000). Research on irrigated cotton systems in Punjab has likewise shown

that technical and environmental performance can be improved through better input mixes (Ullah and Perret, 2014). The positive coefficient for cotton area suggests that farms allocating more land to cotton tend to report higher output, conditional on the other variables in the model. This relationship is consistent with the positive role of cotton area reported by Ashfaq et al. (2012). However, the negative coefficient for total farm size indicates that larger holdings do not necessarily achieve proportionately higher cotton yields. A possible explanation is that management attention, supervision, labour availability, and timely operations become more difficult as the cultivated area expands. This interpretation is plausible but cannot be established from the present model because the study does not directly measure management intensity or labour supervision. Mehmood et al. (2024) similarly show that farm and crop-management characteristics differ between sustainable and conventional cotton producers, reinforcing the need to distinguish total holding size from the area and management devoted specifically to cotton.

The age coefficient is positive (0.032), but its t-statistic (0.381) indicates that the association is not statistically significant. The result does not provide sufficient evidence that farmer age independently influences cotton yield in the sampled farms. Farmers' accumulated experience may nevertheless be valuable when combined with updated technical knowledge on varieties, pest dynamics, and resource management. Extension programmes can build on local experience while introducing evidence-based recommendations (Ullah and Perret, 2014; Adeel et al., 2023).

The negative and statistically significant coefficient for the number of ploughings is consistent with the possibility that repeated tillage raises costs and may not improve soil conditions or crop establishment beyond an agronomically appropriate level. Excessive tillage can increase fuel and machinery expenditure and may disturb soil structure, although the present survey does not directly measure soil physical properties or fuel use. The result is therefore best interpreted as evidence of a negative association in the estimated sample rather than proof that every additional tillage operation reduces yield under all conditions. Extension advice should be based on soil type, field condition, weed pressure, and the locally recommended land-preparation system. Sustainable cotton research in Pakistan has also emphasized the importance of appropriate land preparation and adaptive crop-management practices (Mehmood et al., 2024).

Seed use has a positive and statistically significant coefficient, while the MVP/MFC ratio of 4.46 classifies seed as underutilized under the study's decision rule. Together, these results suggest that the sampled farms may not have been using the economically optimal seed quantity or quality. However, the production-function variable is described as seed quantity (kg), whereas seed quality, germination, varietal purity, and seed treatment are not measured in the model. The result should consequently not be interpreted as evidence that simply increasing seed rate will raise yield. Extension recommendations should distinguish seed rate from seed quality and plant population, and should promote certified, locally adapted seed, appropriate spacing, and calibrated sowing practices. Mehmood et al. (2024) report that registered and stress-tolerant varieties, seed treatment, and gap filling are components of sustainable cotton adaptation practices in Pakistan.

The DAP coefficient is positive (0.056), but its t-statistic (0.974) indicates that the relationship is not statistically significant. The MVP/MFC ratio of 1.50 suggests that DAP was economically underutilized according to the estimated point values. This result should be interpreted as an indication for further attention to phosphorus management rather than a blanket recommendation to increase DAP application. Fertilizer decisions should be based on soil testing, crop nutrient requirements, and balanced nutrient management. Research on cotton production emphasizes the interaction between water and nutrient management in improving input-use efficiency (Wang et al., 2024).

Urea use has a negative but statistically non-significant coefficient and an MVP/MFC ratio of 0.52, which indicates a ratio below unity. This suggests that the estimated marginal value of additional urea at the sample mean is below its marginal cost. The implication is not to eliminate nitrogen fertilizer, which is an essential crop nutrient, but to avoid excessive or poorly timed application. Soil testing, split application, crop-stage-based recommendations, and field demonstrations can help farmers match fertilizer use to crop demand. The need for balanced nutrient management is consistent with the evidence that nitrogen-use efficiency in cotton can be improved by optimizing fertilizer and irrigation interactions (Wang et al., 2024).

The negative, non-significant coefficient for canal irrigation and the negative MVP estimate require particular caution. The result may reflect excessive irrigation, poor timing, waterlogging, differences in canal-water availability, or omitted variation in groundwater use and soil conditions.

The survey measures do not permit these possible mechanisms to be distinguished. Research on cotton in Pakistan has documented inefficiencies in irrigation and groundwater use, with access to extension and training associated with improved technical and environmental performance (Ullah and Perret, 2014; Watto and Mugera, 2015). More recent work published in the target journal also identifies disparities in groundwater efficiency among cotton growers and recommends better water-resource management and farmer education (Khajjak et al., 2024).

The pesticide-spray coefficient is positive but statistically non-significant, while the MVP/MFC ratio of 0.19 indicates that the estimated marginal value of an additional spray is substantially below its cost. This pattern is consistent with the possibility that repeated spraying is not economically justified when applications are not linked to pest scouting and economic thresholds. It does not imply that crop protection is unnecessary; rather, it suggests that the timing and selection of treatments are important. Excessive pesticide use can increase production costs and create occupational and environmental risks (Mancini et al., 2005; Tariq et al., 2007). Extension staff can support integrated pest management through field monitoring, pest identification, threshold-based decisions, and demonstrations. Adeel et al. (2023) specifically examined the working efficiency of extension field staff in relation to cotton IPM in Dera Ghazi Khan, highlighting the extension system's role in communicating crop-protection knowledge.

The classification of laser land levelling as underutilized (MVP/MFC = 1.82) suggests that the estimated value of the additional service may exceed its cost at the sample mean. Laser levelling can improve field uniformity and support more consistent irrigation distribution, but its adoption may be constrained by machinery costs, service availability, farm size, and awareness. The result is consistent with the wider argument that farm-level efficiency depends not only on input quantities but also on access to suitable technologies and advisory support. Evidence from sustainable cotton production in Pakistan documents the use of laser levelling among the suite of management and climate-adaptation practices promoted to improve cotton systems (Mehmood et al., 2024).

The estimated coefficients should be interpreted in relation to the specific variables included in the production function. The negative coefficient for total farm size alongside the positive coefficient for cotton area suggests that overall landholding and land allocated to cotton capture different aspects of farm structure. This distinction is important when interpreting farm productivity: a larger holding does not necessarily imply more intensive or more effective management of the cotton area. Previous research on cotton farms in Punjab has similarly emphasized the role of farm-level resource allocation and management in explaining productivity differences (Ashfaq et al., 2012; Shafiq and Rehman, 2000).

The findings have direct implications for agricultural extension. The input-use ratios point to a need for differentiated recommendations rather than uniform advice to increase or reduce all inputs. Extension agents should help farmers evaluate the marginal return to each major operation, use soil-test-based fertilizer recommendations, schedule irrigation according to crop and field conditions, calibrate seed rates, and adopt pest scouting and threshold-based spraying. This is particularly important because sustainable cotton practices require knowledge, repeated follow-up, and practical demonstrations rather than information delivery alone. Studies in Punjab have linked extension exposure and training with improved technical and environmental efficiency (Ullah and Perret, 2014), while the IJAE study by Khajjak et al. (2024) emphasizes farmer education and resource-management knowledge as part of sustainable groundwater use in cotton production.

CONCLUSION

This study assessed resource-use efficiency among 535 cotton growers in Bahawalpur, Bahawalnagar, Rahim Yar Khan, and Khanewal districts of Punjab, Pakistan. The Cobb–Douglas model explains 33.5% of the variation in cotton yield. Farm size, cotton area, number of ploughings, and seed use show statistically significant associations with yield, while the other included coefficients are not statistically significant. The MVP/MFC ratios indicate potential overutilization of ploughing, urea, canal irrigation, and pesticide sprays, and potential underutilization of laser land levelling, seed, and DAP. Together, these findings point to the importance of improving the timing, quantity, and economic allocation of production inputs.

The central implication is that improving cotton profitability and sustainability requires better input allocation rather than indiscriminate input intensification. Farmers need support to reduce unnecessary tillage and pesticide applications, improve the timing and balance of fertilizer use, apply irrigation according to crop requirements and field conditions, and use appropriate

seed rates and quality seed. Access to laser land levelling and other suitable technologies may also improve resource management where the economic and physical conditions justify their use.

Agricultural extension services should translate these findings into practical, locally adapted programmes. Priority actions include: (i) field demonstrations on calibrated seed rates and plant population; (ii) soil-test-based fertilizer planning and split nutrient application; (iii) irrigation scheduling and water-use monitoring; (iv) integrated pest management based on regular scouting and economic thresholds; (v) demonstrations of laser land levelling and improved land preparation; and (vi) farm budgeting exercises that compare the marginal value of inputs with their costs. Extension workers should use farmer field schools, demonstration plots, mobile advisories, and follow-up visits to reinforce adoption and assess results.

The study contributes farm-level evidence on the use of selected production resources in important cotton-growing districts and identifies practical opportunities for extension services to improve input management. Its findings should be interpreted within the limits of a cross-sectional survey from four purposively selected districts and a single production season. The model does not directly capture all factors that may affect cotton yield, including soil characteristics, varietal differences, weather conditions, pest pressure, irrigation timing, and management skills. Future research should use multi-season data, include additional cotton-growing districts, and incorporate direct measures of extension contact, farmer knowledge, and environmental conditions. Such evidence would help determine how improved resource allocation can raise farm income while reducing pressure on soil, water, and human health.

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