

Article

Adoption and Impact of Integrated Soil Fertility Management Technology on Food Production

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Abstract: Amid recent climate difficulties, integrated soil fertility management (ISFM) strategies are vital in restoring soil fertility, enhancing yield, and achieving the farmer community's well-being. This study examines ISFM's adoption and impact on wheat yields in Punjab, Pakistan, by employing an endogenous switching regression model (ESRM). The selection equation highlights the multiple factors such as age, gender, education, extension access, credit access, and social influence as essential predictors of ISFM adoption. Treatment effects showed that the average wheat yield is higher for adopters. The findings suggest refining the current institutional system will enhance adoption and food security by improving agricultural production.

Keywords: integrated soil fertility management; endogenous switching regression model; yield; Punjab



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1. Introduction

In total, 60% of the world's population depends on agriculture [1]. In many developing countries, such as Pakistan, 70% of the population works in agriculture to provide food, raw materials, and money [2]. Still, despite agriculture's relevance to socio-economic development, agricultural growth has fallen, and this trend is likely to continue endangering the country's food security [3–5]. Pakistan's rural population largely relies on agriculture, but the sector is facing difficulty in attaining maximum production [6,7]. Soil fertility is the leading cause of declining agricultural productivity and poverty in rural households of Pakistan [8]. Severe climate extremities have affected soil moisture levels, while insufficient replenishment and inappropriate soil management have ensued in declining fertility levels [8,9]. Traditional methods for restoring soil fertility and increasing agricultural productivity have become ineffective or disappeared [8]. In addition, the substandard infrastructure that supports agricultural production, both in terms of hard physical facilities and soft service systems, is a significant obstacle to the sector's performance [10,11]. Together with the consequences of climate change, these dangers inhibit the expansion of Pakistan's agricultural economy. The expected climate change, which is forecast to increase in the size and severity of climate-related risks, will impact the productivity of crops such as wheat, rice, and maize [12], and food security as a whole. Thus, applying sustainable intensification approaches has become a dire need of time as it involves enhancing the agricultural production of existing farmland without leading to environmental damage [13–16]. As a core component of sustainable intensification, 'Integrated Soil Fertility Management' (ISFM) has increasingly been endorsed by governments and other relevant agencies [2,17–19]. ISFM is a set of soil management practices that must be applied in contrast with local agroecological conditions [20]. The Alliance for a Green Revolution in Africa (AGRA) defined integrated soil fertility management (ISFM) as a

framework to elevate the production level with a minimum contribution to environmental stress [21]. The ISFM practices are applied in an integrated manner that necessarily includes the usage of chemical fertilizer, improved varieties, and soil organic matter in a combination that prevents soil degradation [22–24]. The basic assumption in the ISFM approach is that each component contributes to soil fertility and productivity, as none can provide sustainable solutions individually. Hence, they should be used in a balanced way [20,25]. Moreover, [26] mentioned some vital aspects of the ISFM approach in developing countries' farming systems. (i) Cautious mineral fertilizer application, (ii) The effective management of available organic matter (animal manure, green manure, crop residues, and compost, and (iii) The protection of soil properties and organic matter. Adopting single practices may not yield the optimal benefits as the literature suggests applying an integrated approach instead of a single practice. Integrating techniques provides sustainable solutions to diverse environmental and social problems [27,28]. Only a handful of studies have explored the impact of natural resource management on crop production and household income [29–31]. However, the determinants of ISFM adoption and its relationship with farm productivity in Pakistan are unknown. Against the current background, this study intends to investigate the factors impacting ISFM adoption among Pakistan's smallholders. Our research adds significantly to the existing body of knowledge. First and foremost, this study is the first to explicitly analyze the predictors of ISFM adoption in Pakistan in the context of interactions between numerous socioeconomic and farm characteristics in a dryland agricultural system. The present research employs an endogenous switching regression model to produce reliable estimates. It extends the literature by providing a micro perspective on ISFM adoption and its impact on Pakistani wheat producers. The study mainly explores two objectives: First, what are certain socio-psychological factors inducing ISFM adoption? Second, how does ISFM affect crop production (wheat yield)? The results of this study will enlighten smallholder farmers, policymakers, and development practitioners on the advantages of using ISFM technology for wheat production.

2. Empirical Framework and Methodology

2.1. Conceptual Model

Figure 1 depicts a decision to embrace a new technology based on relative productivity and risks. Farmers' perceptions of climate stress and benefits are influenced by cognitive abilities, sociodemographic factors, farm characteristics, and institutional factors. Young farmers are more innovative and flexible in trying new things and employing innovative and cutting-edge solutions to climatic and economic problems [32–34]. In contrast, multiple studies report the adverse effects of age on technology adoption decisions [35–38]. Education holds a considerably important position concerning the adoption decisions, as the farmers with better education are likely to have more exposure to innovative ideas, information, and a better skill set [39–41]. Institutional factors disseminate information and awareness about the latest agricultural technologies, such as extension access and organizational membership. Credit access facilitates the purchase of inputs, mainly inorganic fertilizers and improved seed varieties if connected to a well-developed input supply and market access infrastructures [42–44]. Such internal and external factors jointly influence farmers' decisions to adopt ISFM adoption, consequently improving farm production and income.

2.2. Study Area and Data Collection

Punjab is the most populated province and holds a significant share of national agricultural production. Agriculture contributes around three-quarters of Pakistan's exports, while Punjab holds 60% of these exports. Over the years, Punjab has been responsible for meeting food security challenges.

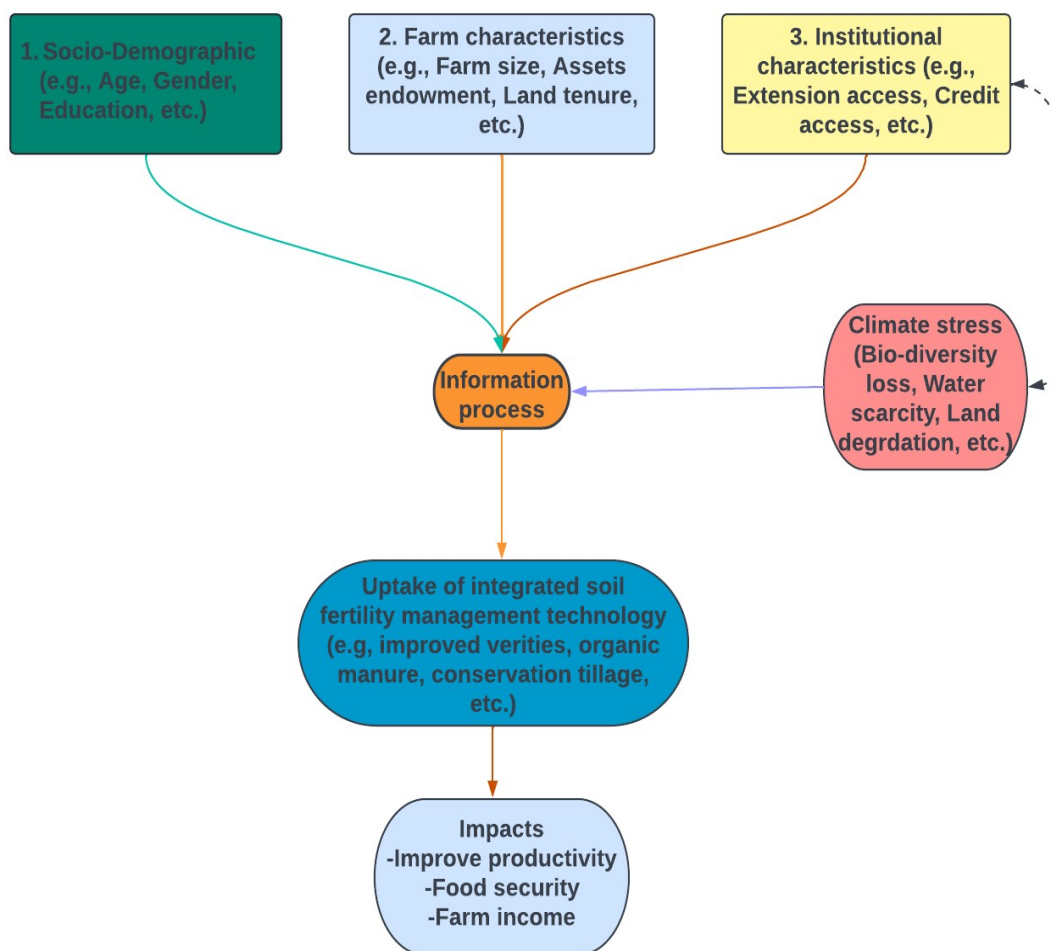


Figure 1. The conceptual framework for the study.

Wheat is the most cultivated crop with a 40% share, followed by other crops with 60% [45]. The surveyed districts in Figure 2 carry diversity and inclusion, enhancing generalizability and reducing location-specific limitations. The study is based on primary datasets collected through a well-organized and comprehensive survey. The survey employed multi-stage random sampling to collect the total sample size of 666 farmers from three representative districts.

$$n_0 = \frac{Z^2 pq}{e^2} 666 = \frac{(2.58)^2(0.5)(0.5)}{(0.05)^2} \tag{1}$$

As the total population of the farmers residing in the Punjab region is unknown, we employed the Cochran formula in Equation (1) to determine the sample size based on the empirical evidence [46–48].

As expressed in Figure 3, the following elements are selected in a sequence at each stage. Firstly, the Punjab province is the leading study region. Secondly, four districts were selected based on homogeneity, climate, and cropping pattern, and a random sampling technique was applied. Further, two tehsils (sub-districts) from each district employ a simple random sampling technique, and four to five union councils from each of the tehsils use the random sampling technique. Consequently, in the next stage, two to three villages were randomly selected from each union council; lastly, around five to seven farmers were selected from each of the villages.



Figure 2. Map of the study area.

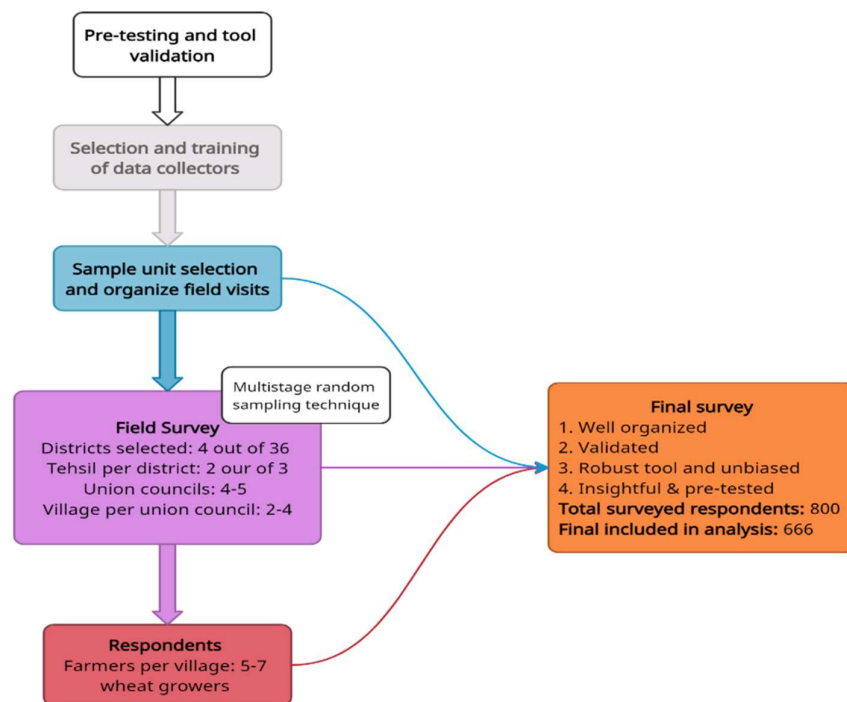


Figure 3. Sampling framework of the study.

2.3. Endogenous Switching Regression Model (ESRM)

The current study employed the endogenous switching regression model (ESRM), consisting of two steps. The first step involves the decision to adopt ISFM technology or not, whereas the second step deals with the outcome of ISFM adoption. It is assumed that farmers are risk neutral, and their decision for technology adoption will be influenced by the utility they will derive from adoption. As the ISFM aims to enhance soil nutrients, we used farm production as the outcome indicator. Based on the suggestion of [49,50], we employed the endogenous switching regression model of farm productivity as follows:

$$d_i = \begin{cases} 1 & \text{if } \gamma z_i > u_i \\ 0 & \text{if } \gamma z_i \leq u_i \end{cases} \tag{2}$$

where the d_i is a latent observed variable determined by both unobserved and observed factors that determine which regime the farmer falls.

The latent equation for d_i is given by:

$$d_i^* = \gamma Z_i + u_i \tag{3}$$

Whereas the outcome equation for each of the farmer positions is given below:

$$\text{Regime 1 : } y_{1i} = \beta_1 X_{1i} + \varepsilon_{1i} \tag{4}$$

$$\text{Regime 2 : } y_{2i} = \beta_2 X_{2i} + \varepsilon_{2i} \tag{5}$$

In the equations mentioned above, the y_{ji} is the response variable in the outcome equation, while the X_{1i} and X_{2i} are the vectors of exogenous variables, while ε_{1i} , ε_{2i} , and U_i are parameters to estimate. The trivariate normal of distribution is assumed amongst the error terms. The covariance matrix and zero mean are denoted by sigma (σ), as explained below.

$$\sigma = \text{cov}(\varepsilon_{1i}, \varepsilon_{2i}, \mu_i) = \begin{bmatrix} \sigma^2 \varepsilon_1 & \cdot & \sigma \varepsilon_1 \mu \\ \cdot & \sigma^2 \varepsilon_2 & \sigma \varepsilon_2 \mu \\ \cdot & \cdot & \sigma^2 \mu \end{bmatrix} \tag{6}$$

In the equation mentioned above, $\sigma^2 u$ is taken as the covariance of the error term in the selection. Whereas the error term variances in the farm income effect function are taken as $\sigma^2 \varepsilon_1$ and $\sigma^2 \varepsilon_2$, whereas ε_{1u} and $\sigma \varepsilon_{2u}$ signify the covariance of u_i , ε_{1i} , and ε_{2i} . Consequently, the expected values ε_{1i} and ε_{2i} are non-zero [33]:

$$E[\varepsilon_{1i} | d_i = 1] = \sigma \varepsilon_{1u} \frac{\varnothing(\beta x_i)}{\Phi(\beta x_i)} = \sigma \varepsilon_{1u} \lambda_{1i} \tag{7}$$

$$E[\varepsilon_{2i} | d_i = 1] = \sigma \varepsilon_{2u} \frac{\varnothing(\beta x_i)}{1 - \Phi(\beta x_i)} = \sigma \varepsilon_{2u} \lambda_{2i} \tag{8}$$

In the equation mentioned above, $\Phi(\cdot)$ is the standard normal probability function, while the standard normal cumulative density function $\Phi(\cdot)$ and $\lambda_{1i} = \frac{\varnothing(\beta x_i)}{\Phi(\beta x_i)}$, $\lambda_{2i} = \frac{\varnothing(\beta x_i)}{1 - \Phi(\beta x_i)}$. Consequently, it follows that the covariance's $\sigma \varepsilon_{1u}$ and $\sigma \varepsilon_{2u}$ are statistically significant, and the decision of ISFM adoption and yield outcome are correlated. Hence, it is enough for the endogenous switching regression and the rejection of the null hypothesis for the selection bias. The ESRM is estimated through the full information maximum likelihood (FIML) of the wheat yield and constant standard error; firstly, estimating the selection equation (probit criterion) and then following through regression equation.

$$\text{LnLi} = \sum_{i=1}^N \left[\text{Ln} \varnothing \left(\frac{\varepsilon_{1i}}{\sigma \varepsilon_1} \right) - \text{Ln} \sigma \varepsilon_1 + \text{Ln} \Phi(\varphi_{1i}) \right] + (1 - d) \left[\text{Ln} \varnothing \left(\frac{\varepsilon_{2i}}{\sigma \varepsilon_2} \right) - \text{Ln} \sigma \varepsilon_2 + \text{Ln}(1 - \Phi(\varphi_{2i})) \right] \tag{9}$$

$$\text{where } \varphi_{ji} = \frac{(\beta x_i + \gamma j \varepsilon_j \sigma_j)}{\sqrt{1 - \gamma^2}}, j, i = 1, 2$$

where γ represents the correlation coefficient amongst the error terms u_i of the selection and the error term of ε_{ij} of the equations. The ESRM was used to compare the potential wheat production amongst the technology adopters and non-adopters and to investigate the possible production levels in counterfactual hypothetical cases in adopters who did not adopt and non-adopters who adopted. The effect of the treatment ISFM technology adoption on the treated (adopters) (ATET) was calculated as follows:

$$ATT = E[Y_{1i}|d_i = 1] - E[Y_{2i}|d_i = 1] = X_{1i}(\beta_1 - \beta_2) + \lambda_{1i}(\sigma\varepsilon_{1i}u - \sigma\varepsilon_{2i}u) \quad (10)$$

Similarly, the effect of the treatment on the untreated (ATU) for non-adopters was calculated as the difference between as follows:

$$ATU = E[Y_{1i}|d_i = 0] - E[Y_{2i}|d_i = 0] = X_{1i}(\beta_1 - \beta_2) + \lambda_{2i}(\sigma\varepsilon_{1i}u - \sigma\varepsilon_{2i}u) \quad (11)$$

2.4. Variable Specification

The study utilizes the data of 666 farmers to investigate the impact of ISFM adoption on crop production. ISFM adoption is subject to numerous factors, and based on a literature review [51–55], the current study characterized these factors as household, farm level, and institutional and environmental characteristics. The household's characteristics involve the variables (age, gender, household size, education) that affect ISFM technology adoption, consisting of categorical and continuous variables. Age is taken as a number of years, and gender is used as a dummy variable with 1 = male and 0 otherwise. Household size is a continuous variable with the number of family members. Education is also considered the dummy variable with 1 = 10 years of formal education and 0 = otherwise. Farm-specific variables consist of farm size, assets index, and land tenancy. Farm size is a continuous variable with the number of acres the farmers operate. We used the wealth factors as the composition of the household assets index, such as (tillage machinery, livestock, tractors, sprayer, and car). A PCA analysis was conducted to compose the wealth index. Considering the crucial role of wealth, financial soundness is often described as the foundation of technology adoption [40]. Multiple studies have highlighted the role of asset accumulation on household adoption decisions [40,41,56]. Institutional access holds the utmost importance in disseminating information to persuade farmers to adopt the latest agricultural technology. Organizational membership, extension access, and credit access were taken as the main facets of institutional access; all were dummy variables. Based on the literature review [2,47,57–61] and local context, we chose three soil management technologies (chemical fertilizer, improved varieties, and soil organic matter) broadly defined as ISFM and taken as the dummy variable.

3. Results and Discussion

3.1. Descriptive Statistics

The descriptive statistics in Table 1 revealed that the average age for this study was 42, with 92% predominantly male and 47% attaining ten years of formal education. Amongst the farm characteristics, the average farm size was 4.10 acres, and 88% were farm owners.

Table 1. Descriptive statistics and definition of the variables.

Variable		Mean	S. D
ISFM adoption	1 = If the farmer adopts ISFM technology, 0 = Otherwise	0.452	0.421
Wheat production	Wheat production per acre (Log)	7.011	0.226
Age	Age number of years	42.812	8.530
Gender	Farmer is male (1 = yes; 0 = no)	0.921	0.268
Education	1 = If the farmer attained ten years of formal education, 0 = Otherwise	0.572	0.499
Family size	Total family members	8.248	5.154
ICT usage	1 = If the farmer uses information and communication technology (ICT) user, 0 = Otherwise	0.536	0.409
Social influence	1 = If neighboring farmers adopt ISFM Technology, 0 = Otherwise	0.502	0.500
Non-farm participation	1 = If the farmer participates in non-farm Activities, 0 = Otherwise	0.331	0.472
Farm ownership	1 = If the farmer is the owner of the land, 0 = Otherwise	0.884	0.320
Farm size	Land under cultivation, acres	4.109	0.775
Assets index	Assets index of the farm households	6.421	2.029
Organizational membership	1 = If the farmer is a member of any association, 0 = Otherwise	0.524	0.439
Extension access	1 = If the farmer has accessed extension services, 0 = Otherwise	0.338	0.473
Credit access	1 = If the farmer has accessed credit, 0 = Otherwise	0.583	0.401
Drought experience	1 = If the farmer experienced production shock, 0 = Otherwise	0.416	0.413

Around 33% of the farmers have allocated the labor for off-farm activities. Amongst the institutional characteristics, almost 58% of the farmers had accessed credit in the past year, while 33% accessed an agricultural advisory in the past twelve months. Moreover, 52% of the farmers were members of any FOs, and 53% had access to information and communication technologies (ICT). In comparison, 41% of the farmers have experienced seasonal shocks in recent years.

3.2. FIML Estimates of the ESRM—Determinants of ISFM Technology Adoption among Smallholders

This study used an ESRM to control for biases that could confound the results. The initial segment of Table 2 centers around the determinants that impact the adoption of ISFM technology. The factors responsible for ISFM adoption are education, non-farm participation, organizational membership, extension access, and social influence. To begin with, the farmer’s characteristics reported in the education coefficient are positive and significant, showing the direct effects of education on farmers’ adoption decisions. Higher formal education helps farmers to use their natural resources efficiently. Education is crucial in creating awareness about improving the farmers’ execution level [28,62]. Likewise, [63] supported education’s significant and positive impact on ISFM adoption. Assuming lost labor effect from farming operations, the results signify a negative relationship between off-farm participation and ISFM adoption. Likewise, refs. [64,65] reported an inverse association between off-farm participation, labor productivity, and farm investment. Similarly, ref. [66] reported that off-farm participation is inversely related to farmers’ decisions to invest in soil and water conservation practices in China’s loess plateau.

Table 2. Full information maximum likelihood (FIML) of ESRM model.

	Selection	Log Yield	
		Non-Adopter	Adopters
Age	0.002(0.008)	−0.001(0.001)	−0.001(0.001)
Gender	−0.040(0.238)	0.045(0.029)	−0.007(0.029)
Family size	−0.023(0.014)	0.003 *(0.001)	0.001(0.001)
Education	1.301 *** (0.225)	−0.003(0.028)	−0.050(0.054)
Non-farm participation	−1.095 *** (0.259)	−0.001(0.017)	0.038(0.048)
Social influence	1.224 *** (0.239)		
ICT user	0.025(0.129)	0.078 *** (0.016)	0.069 *** (0.015)
Farm size	−0.029(0.083)	0.003(0.010)	0.003(0.010)
Assets index	0.023(0.030)	−0.002(0.004)	0.001(0.003)
Farm ownership	−0.185(0.203)	−0.023(0.024)	−0.009(0.024)
Extension access	0.331 ** (0.142)	0.035 *(0.019)	0.030 *(0.016)
Organizational membership	1.366 *** (0.125)		
Credit access	−0.042(0.129)	0.023(0.016)	0.038 ** (0.015)
Drought experience	0.110(0.126)	−0.023(0.015)	−0.030 ** (0.015)
Constant	−1.119 ** (0.485)	7.055 *** (0.062)	7.101 *** (0.058)
lns1	−1.910 *** (0.043)		
lns2	−2.044 *** (0.041)		
r1	−0.404 ** (0.198)		
r2	0.138(0.161)		
sigma_1	0.147(0.006)		
sigma_2	0.129(0.005)		
rho_1	−0.383(0.169)		
rho_2	0.137(0.158)		
chi2(1) =	5.82 **		
Log-likelihood =	108.235		
Wald chi2(12) =	52.55 ***		

***, **, and * indicate significance at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

The coefficient of organizational membership is significant and positive, indicating that organizational members are more likely to adopt ISFM technology. Organizational membership is beneficial for disseminating the introduction and execution of the latest farming technologies. Likewise, Mazhar et al. (2020) [67] reported a significant and positive impact of organizational membership concerning soil management technologies. The extension access is significantly and positively related to the farmer's ISFM adoption decisions. Moreover, farmers with access to extension services were more likely to adopt ISFM practices. Likewise, refs. [68,69] also reported the significant role of extension access in influencing the ISFM adoption decisions. The coefficient of social influence is positive and significantly related to ISFM adoption as the information passed from one farmer to another stimulates the adoption process through shared knowledge [70]. Similarly, Case (1992) [71] suggests that hearing about specific technology and adopting it involves multiple interrelated factors, and the neighborhood effect is one of those crucial determinants. Correspondingly, Mazhar et al. (2020) [67] found a positive impact of social influence on farmers' technology adoption decisions.

3.3. Effect of ISFM Technology Adoption on Wheat Productivity of Smallholders

The Wald test is highly significant, indicating the model's fit well. The results specify the occurrence of self-selection, thus justifying the application of the endogenous switching regression model [49,68]. The likelihood ratio test at 1% for joint independence of the three equations suggested they should not be estimated separately. We may reject the null hypothesis of no link between ISFM adoption and wheat yields based on the likelihood ratio test implying that ISFM adoption increases wheat yields.

The second stage of the ESRM estimates the impact of ISFM adoption on farm production (adopters and non-adopters). Household size, ICT usage, farmer association membership, and drought experience explain differences in farm productivity.

The coefficient of household size was significant and positive, reflecting that households with more members tend to have higher productivity. Farm labor comprises the considerable production cost of agriculture; thus, the lack of labor availability impedes the adoption of soil management techniques and has an inverse impact on farm productivity [36,37,72].

The results showed a significant positive relationship between ICT usage and wheat yield amongst adopters and non-adopters. ICTs facilitate technology adoption, transmit information, improved inputs, new markets, and low-cost market prices, thus contributing to agricultural productivity. Likewise, Lio et al. (2006) [73] support the significant role of ICT in enhancing productivity.

Access to credit was significantly and positively related to productivity for adopters. Credit arrangements are crucial in arranging the finance required concerning capital-intensive agriculture technology and facilitating agriculture productions, consistent with Abdulai et al. (2014) [68]. Drought experience appears to have adverse effects on crop productivity for non-adopters. Likewise, Adego et al. (2019) [74] reported the reduction in maize yield due to drought-related events, thus affecting farm income.

Table 3 represents the results considering the effects of the average treatment (ATT); the findings signify the positive and significant impact of ISFM adoption on wheat yields. The ATT estimates counter the selection bias considering that the adopters and non-adopters can be systematically different. The causal effect of ISFM adoption shows a substantial increase in wheat production for the adopters. The findings are consistent with [75,76] and support technology adoption's significant role in improving farm production and household welfare.

Table 3. Impact of ISFM adoption on log farm production.

Mean Outcome Log Farm Production				
	Adopters	Non-Adopters	Difference	T-Value
ATT	7.39	6.85	0.54 ***	8.33

*** indicate significance at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

4. Conclusions

Current research has established the importance of ISFM technology by explaining its adoption and impact on wheat production amongst smallholders in Punjab, Pakistan. Based on farm-level data, the study employed an endogenous switching regression model to estimate productivities amongst adopters and non-adopters of ISFM technology. The findings showed the significance and impact of education, extension access, organizational membership, production shock, and social influence on ISFM adoption. The consequent effect of the determinants, such as extension access, ICT usage, credit access, and drought-experience translates into increased wheat productivity for the adopters of ISFM technology. Factors such as household size, extension access, and ICT were the main determinants of productivity for the non-adopters. The treatment effect showed that ISFM technology mitigates the hazardous environmental impact and enhances productivity. The findings propagate the solid implications for ISFM adoption and elevating farm production. The results suggest effective measures to improve ISFM adoption, thus improving education, credit access, extension access, climate change information, and strengthening the social network. Government and farmers should take the lead in promotion and diffusion at the initial stages to ensure the effective adoption and dissemination of new conservation technologies. However, despite the possibility that ISFM may increase wheat output, this alternative may be expensive to adopt and may not be in line with other societal and environmental goals. Future research should therefore investigate the impact of ISFM on society and the environment.

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