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ADOPTION OF SEED MANAGEMENT PRACTICES AND ITS IMPACT ON WHEAT PRODUCTIVITY: EVIDENCE FROM PUNJAB, PAKISTAN

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Abstract

Seed management practices—referred to as seed treatment, storage, and timely replacement—are critical for improving crop quality, enhancing wheat productivity, and ensuring food security. Despite initiatives started by public and private institutions in Pakistan to promote these practices, their adoption among wheat farmers is often limited. This study investigated the adoption of seed management practices in Punjab province and their impact on wheat productivity. Wheat farmers were approached for data collection in Sheikhupura district using a structured questionnaire and convenience sampling method. Descriptive analysis was carried out with the help of SPSS 26, while relationships between variables were assessed using Partial Least Squares Structural Equation Modelling (PLS-SEM). The results of the analysis indicated that the adoption of seed management practices was significantly affected by technical attributes, institutional support, financial constraints, and access to information. In contrast, marketing factors did not exhibit a significant impact. Additionally, it was discovered that the adoption of these practices had a statistically significant and positive effect on wheat productivity. The study highlights the need for targeted interventions such as improved farmer training, enhanced access to certified seeds, and investment in storage infrastructure to strengthen seed systems and promote adoption. These findings provide crucial empirical evidence that can guide policymakers and agricultural stakeholders in designing effective strategies for sustainable wheat production and rural development. This study provides localized evidence on wheat seed management practices in Punjab. It contributes by analysing technical, institutional, financial, and informational factors of adoption. Practical value lies in highlighting farmer training, certified seed access, and storage improvement. The findings offer policy insights for sustainable wheat productivity and rural development.

Keywords: Seed Management Practices, Adoption, Productivity, Impact, Wheat, Factors

1. Introduction

Seed management practices refer to all activities related to selecting, treating, storing, and replacing seeds to ensure high germination rates, strong crop establishment, and maximum yield potential (Noor et al., 2026). These practices include using certified seeds, applying chemical or biological treatments, storing seeds under proper conditions, and replacing old seed stocks regularly (Kumar et al., 2023). In Pakistan, seed management is crucial for wheat production, as wheat is a staple food crop. Many farmers still rely on farm-saved seeds, but government and private sector efforts are promoting certified seed use, modern storage techniques, and timely replacement to enhance productivity (Hussain et al., 2017).

In developed countries like China, South Korea, the USA, Japan, and Australia, seed management is highly advanced. Farmers follow strict quality control standards, employ precision seed treatments, use climate-controlled storage, and adopt regular replacement cycles. These measures are backed by strong research systems, mechanization, and seed certification laws, ensuring high productivity and resilience (Yu et al., 2023; Solberg et al., 2020). In Asia, especially in South Asia's agricultural economies, seed management is central to food security. Countries like India, Bangladesh, and Nepal face similar challenges—low adoption of certified seeds, poor storage conditions, and limited farmer awareness (Beshir, 2024).

Globally, seed management practices are recognized as one of the most cost-effective ways to improve crop yields and resilience. Advanced economies employ strict quality standards, advanced seed treatments, and modern storage systems, while developing regions focus on awareness campaigns and infrastructure improvement (Okori et al., 2022). From the farmer's perspective, good seed management means better germination, uniform crop stands, reduced pest and disease risks, and ultimately higher and more stable income. Seed treatment protects seeds from early-stage pests and diseases, improving plant survival and reducing the need for later pesticide use (Lamichhane et al., 2022). Seed replacement ensures that genetic purity and vigor are maintained, leading to stronger, higher-yielding plants (Qian et al., 2017; Eshete et al., 2021). Seed storage preserves seed quality between seasons, reducing losses from moisture, pests, or other factors.

1.1 Study Objectives

1. Identify the existing seed management practices of the wheat farmers.
2. Identify factors affecting the adoption of improved seed management practices.
3. Determine the impact of adoption of seed management practices on wheat productivity.
4. Suggest suitable recommendations needed to promote adoption of seed management practices among the farming community in Punjab province, Pakistan.

2. Literature Review

High-quality seeds are a cornerstone of crop productivity and food security, particularly in developing countries. Empirical studies report yields gains of 20 to 30 percent with the adoption of improved seed varieties (Afzal et al., 2016). However, the benefits of improved seeds can be compromised by environmental stress during germination and early plant development (Zinsmeister et al., 2020). Seed treatments, whether chemical, biological, or physical, play a critical role in protecting seeds against pests and diseases, thereby supporting healthier crop establishment and improved yield potential (Ayesha et al., 2021).

Modern seed treatments have evolved significantly, incorporating fungicides, insecticides, and micronutrients like zinc and boron to enhance vigor and disease resistance (Munkvold, 2009). While these treatments improve seedling performance, their impact on final yield is not always consistent (Freiberg et al., 2017). In response to environmental and health concerns, there is growing interest in biological and eco-friendly alternatives (Moumni et al., 2020).

Seed replacement—using certified or hybrid seeds instead of farmer-saved seed—is vital for maintaining genetic purity and productivity. Yet, Pakistan's wheat seed replacement rate remains low at around 20 percent (FSCRD, 2023), hindered by limited seed availability, high costs, and low awareness (Singh et al., 2023). Even slight improvements in SRR can enhance yields by approximately 22 kg/ha (Hoque & Biswas, 2024).

Storage conditions also critically influence seed quality. High humidity, pest attacks, and heat exposure degrade seed viability (Blum & Bekele, 2018). Although many Pakistani farmers store wheat seed on-farm, effective storage techniques are uncommon. Moisture levels above 14 percent accelerate deterioration (Martin et al., 2022), but affordable innovations like drying beads and vacuum sealing offer practical solutions (Motis, 2019).

Seed systems in Pakistan function through both formal and informal channels. While formal systems ensure quality control, they fail to reach most smallholders, who depend on informal sources for up to 90 percent of their seed needs (FAO, 2018). Community-Based Seed Systems (CBSS) offer a hybrid approach to improve access and resilience (PELUM, 2016).

Adoption of improved seed practices is influenced by socioeconomic factors such as education, farm size, income, and institutional access (Gemechu & Bekele, 2023). Addressing barriers like poor extension services and limited awareness is essential to strengthening seed systems and boosting productivity in Pakistan.

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Seed quality is a critical driver of agricultural productivity, food security, and sustainability. High-quality seeds enhance germination, plant vigor, resistance to pests and diseases, and overall yields (Zinsmeister et al., 2020). Seed treatments, whether chemical, biological, or physical, offer early-stage protection and reduce reliance on pesticides by improving crop establishment (Lamichhane et al., 2022). However, adoption of such practices remains low among smallholders in developing countries due to limited resources and awareness.

Equally important is proper seed storage. Inadequate infrastructure and traditional methods expose seeds to pests, moisture, and heat, significantly reducing their viability (Santos et al., 2016). In tropical regions like Pakistan, climatic conditions exacerbate these issues, while access to modern storage technologies remains limited (Saeed et al., 2020). Traditional storage techniques, including the use of cow dung, plant powders, or clay pots, vary in effectiveness and often lack standardization (Mathad et al., 2013). Ahmed et al. (2025) suggested that people may change their behaviour based on risk attitudes influencing economic decision-making while facing economic uncertainty.

Seed replacement, defined as the regular use of certified seed, ensures genetic purity and disease resistance. Yet, in Pakistan and other developing countries, seed replacement rates remain low due to seed unavailability, financial constraints, and weak institutional support (Singh et al., 2023). Even a one percent increase in the seed replacement rate can boost yield by over 20 kilograms per hectare (Bhandari et al., 2021).

Adoption of seed management practices is influenced by several key factors. Technical attributes such as pest resistance and seed viability significantly affect farmers' choices (Bilal & Jaghdani, 2024). Financial access, including credit and flexible payment systems, enables investment in improved inputs (Larik et al., 2024). Marketing support through labelling, price incentives, and demand signals encourages adoption (Hussain & Maharjan, 2025). Institutional services, including extension programs and training, improve knowledge and facilitate technology use (Yitayew et al., 2021). Finally, informational access through timely and reliable sources influences awareness and decisions (Luqman et al., 2024).

Table 1
Measurement Construct of the Scale

Construct	Source	Measurement	Total No. of Items
Wheat productivity	Zhang & Li, 2021	Direct/Observed	3
Adoption of seed management practices	Kumar, 2024; Yigezu et al., 2021; Hussain & Maharjan, 2025	Reflective	9
Technical attributes	Awotide et al., 2016	Reflective	4
Marketing parameters	Pingali et al., 2019	Reflective	3
Financial consideration	Abate, 2024	Reflective	3
Informational access	Adebayo Aminu et al., 2021	Reflective	3
Institutional services	Dias et al., 2020	Reflective	4

Note. Adapted from the cited sources.

While individual studies support these relationships, findings remain context-specific. Therefore, further investigation is required to assess how these factors jointly influence adoption behaviour and wheat productivity in Punjab, Pakistan.

3. Research Framework

Grounded in Rogers' Diffusion of Innovations Theory (2003), this study models seed treatment, replacement, and storage as dependent on a combination of technical, financial, institutional, marketing, and informational factors. These adoption decisions, in turn, are hypothesized to drive improvements in wheat productivity.

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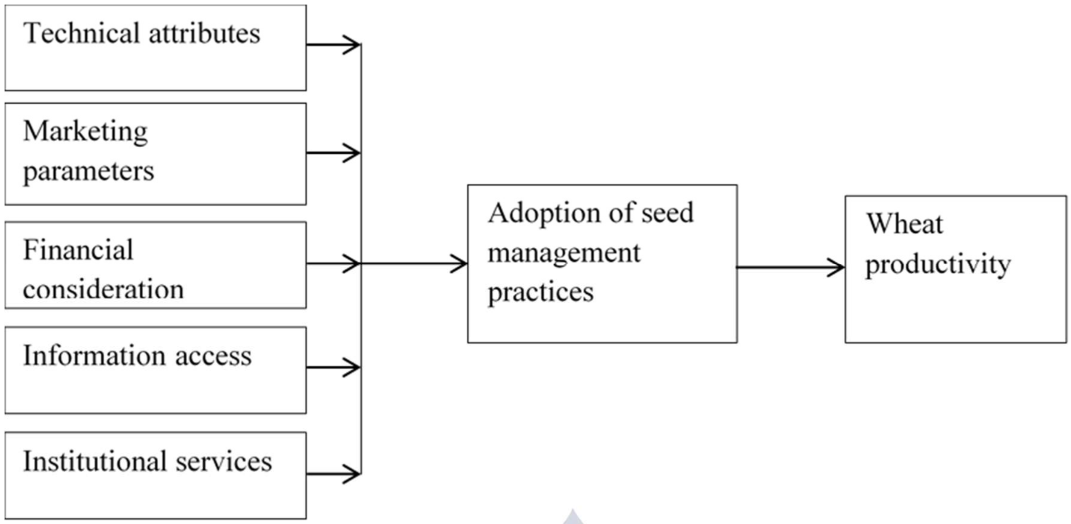
Figure 1
Research Framework



Note. The figure presents the hypothesized relationships among technical attributes, marketing parameters, financial consideration, information access, institutional services, adoption of seed management practices, and wheat productivity. Adapted from the study framework.

4. Methodology

4.1 Sampling Design and Research Tool

Keeping the study objectives and hypotheses in mind, this research incorporated a quantitative method. The data were collected from farmers—both male and female—aged 18 years or above from April 2025 to May 2025. The reason to choose this age bracket was that farmers (male or female) are more likely to be involved in decision-making related to wheat seed management practices, given Pakistan's cultural and working-age context (Department of Labor and Manpower, Govt. of Pakistan, 2018); moreover, those stand rational enough to understand the future benefits of adoption of these seed management practices. Farmers were purposely contacted, and approval was sought to present the questionnaire. Afterward, the 177 filled questionnaires were collected from the respondents and used for further data analysis.

4.2 Demographics of Respondents

The instrument includes nine demographic indicators to assess key characteristics of the respondents, namely: education level, gender, age, marital status, family size, farming experience, major source of income and occupation other than farming, and landholding size. These variables are critical for understanding the socio-economic context influencing farmers' engagement with institutional services and seed management practices (Kassie et al., 2015). The inclusion of these indicators enables the analysis of how personal and household factors shape access to extension services, decision-making authority, and the ability to adopt improved agricultural practices.

4.3 Measures

The variable measures having high internal consistency were adapted from previous studies and modified according to the current study. Wheat productivity was adapted and modified from Khan et al. (2020), Zhang and Li (2021), and Ahmed et al. (2024). Seed management practices were adapted and modified from Ahmed et al. (2024), Sindhuja et al. (2024), Dadlani et al. (2023), Trail et al. (2021), Afzal et al. (2016), Marahatta et al. (2021), Khalid et al. (2024), and Afzal et al. (2020). Technical attributes were adapted and modified from Pervaiz et al. (2023), Lamichhane et al. (2022), and Usman et al. (2024). Marketing parameters were adapted and modified from Singh et al. (2020) and Jalal-Ud-Din et al. (2024). Financial consideration was adapted and modified from Khan and Verma (2016), Bilal and Jaghdani (2024), and Makate et al. (2024). Informational access was adapted and modified from Okori et al. (2022), Ullah et al. (2022), and Orifi (2018). Institutional services were adapted and modified from Bilal et al. (2015) and Sadaf et al. (2021). This study used a five-point Likert scale for all item responses ranging from 1—strongly disagree to 5—strongly agree. Pre-testing was performed among 51 respondents before data were collected to test the validity and reliability of the questionnaire. All of the measures showed high internal consistency; furthermore, no issue was found regarding the respondents' understanding. The questionnaire was designed in English. In line with Asif et al. (2018), the present study distributed the questionnaire in the English language to the respondents without translating it to the national language of Pakistan, i.e., Urdu.

5. Data Analysis and Results

5.1 Measurement Model Assessment

For analysis purposes, in SPSS, the constructs were coded as follows: Wheat productivity as WP, adoption of seed management practices as ASMP, technical attributes as TA, marketing parameters as MP, financial consideration as FC, information access as InfA, and institutional services as IS. Moreover, for structural equation modelling (SEM), the data were analysed using SmartPLS-4. All of the constructs' composite reliability (CR) values ranged from 0.710 to 0.929, showing that reliability for all of the constructs exists. The average variance extracted (AVE) for all of the constructs remained above 0.50 (see Table 2 for item loadings, composite reliability, and AVE values).

Table 2

Measurement Model Assessment: Loadings, Composite Reliability, and Average Variance Extracted

Construct	Items	Loadings	CR	AVE
Wheat productivity	WP1	.899	.792	.699
	WP2	.719		
	WP3	.878		
Adoption of seed management practices	ST1	.783	.929	.638
	ST2	.839		
	ST3	.850		
	SR1	.814		
	SR2	.813		
	SR3	.834		
	SS1	.674		
	SS2	.783		
	SS3	.786		
Technical attributes	TA1	.690	.794	.618
	TA2	.734		
	TA3	.760		
	TA4	.719		
Marketing parameters	MP1	.757	.835	.664
	MP2	.785		
	MP3	.710		
Information access	Inf1	.842	.718	.619
	Inf2	.764		
	Inf3	.747		
Institutional services	IS1	.746	.710	.617
	IS2	.759		
	IS3	.814		
	IS4	.698		
Financial consideration	FC1	.845	.727	.660
	FC2	.760		
	FC3	.622		

Note. CR = composite reliability; AVE = average variance extracted.

For the validity test, the Heterotrait-Monotrait Ratio (HTMT) test was conducted, and the result showed that all of the values were below 0.90, which establishes the scale validity (Henseler et al., 2015). While Tables 3 and 4 confirm the establishment of reliability and discriminant validity, Table 5, showing variance inflation factor (VIF) values, proves that the issue of multicollinearity does not exist.

Table 3

Reliability Analysis

Construct	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Technical attributes	.790	.794	.618
Marketing parameters	.834	.835	.664
Financial facts/consideration	.702	.727	.660
Information access	.707	.718	.619
Institutional services	.745	.710	.617
Adoption of seed management practices	.928	.929	.638
Wheat productivity	.779	.792	.699

Table 4

Heterotrait-Monotrait Ratio (HTMT)

Construct	ASMP	FC	IS	InfA	MP	TA	WP
ASMP	—						
FC	.840	—					
IS	.530	.892	—				
InfA	.840	.677	.745	—			
MP	.606	.680	.705	.906	—		
TA	.811	.753	.776	.904	.898	—	
WP	.785	.548	.562	.814	.654	.812	—

Note. ASMP = adoption of seed management practices; FC = financial consideration; IS = institutional services; InfA = information access; MP = marketing parameters; TA = technical attributes; WP = wheat productivity. All HTMT values were below the .90 threshold (Henseler et al., 2015).

Table 5

Variance Inflation Factor (VIF)

Predictor	VIF
ASMP → WP	1.000
FC → ASMP	2.128
IS → ASMP	2.140
InfA → ASMP	2.305
MP → ASMP	2.460
TA → ASMP	1.956

Note. ASMP = adoption of seed management practices; WP = wheat productivity; FC = financial consideration; IS = institutional services; InfA = information access; MP = marketing parameters; TA = technical attributes. All VIF values were below 5, indicating no multicollinearity concerns.

The R-square value (Table 6) of adoption of seed management practices and wheat productivity remained at 0.461 and 0.458 respectively, which shows the explained variance is substantial (Cohen, 1988), and hence shows the model's predictive capability.

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Table 6
Explained Variance

Endogenous Latent Variable	Variance Explained (R^2)
ASMP	.461
WP	.458

Note. ASMP = adoption of seed management practices; WP = wheat productivity.

5.2 Analytical Method and Hypothesis Testing

Structural Equation Modelling (SEM) was employed to test the proposed hypotheses (Table 7). SEM can be implemented through two primary approaches: variance-based and covariance-based techniques. Covariance-based SEM (CB-SEM) is generally suitable for reflective measurement models and is not designed to accommodate formative models. Jong et al. (2005), in a comprehensive literature review, emphasized that many studies mistakenly treated formative indicators as reflective, which compromises the validity and practical relevance of their findings. To address this issue, the Partial Least Squares (PLS) approach, a variance-based technique, has gained popularity across various disciplines for its effectiveness in handling both formative and reflective measurement models (Henseler et al., 2009).

Based on the literature, the following hypotheses are proposed:

Table 7
Research Hypotheses

Code	Hypothesis	Source/Supportive Studies
H1	Financial consideration positively affects adoption of seed management practices.	Larik et al., 2024; Abate, 2024; Rayhan et al., 2023; Yu et al., 2024
H2	There is a positive relationship between information access and adoption of seed management practices.	Ahmed et al., 2024; Luqman et al., 2024; Sheikh et al., 2016
H3	Institutional services negatively affect adoption of seed management practices.	Hussain & Maharjan, 2025; Saeed et al., 2022; Baglan et al., 2020
H4	Marketing parameters positively affect adoption of seed management practices.	Zia et al., 2024; Hussain & Maharjan, 2025; Dadlani et al., 2023
H5	Technical attributes positively affect adoption of seed management practices.	Buyela et al., 2024; Bilal & Jaghdani, 2024; Cardarelli et al., 2022
H6	Wheat productivity is positively influenced by adoption of seed management practices.	Mdlaose et al., 2022; Lollato et al., 2022; Lamichhane et al., 2022

Table 8 shows the testing of the direct relationships among variables (H1 to H6). Financial consideration positively affected adoption of seed management practices with beta 0.159 and *p* = 0.005 values, which led to the acceptance of the first hypothesis. Furthermore, information access relationship with adoption of seed management practices indicated a 0.362 beta value with 0.000 *p*-values that proved significantly positive; therefore, the second hypothesis is also accepted. Institutional services were positively related to adoption of seed management practices with beta 0.027 and *p* = 0.293 values; so, the third hypothesis is not accepted. Marketing parameters were positively related to adoption of seed management practices with beta 0.192 and *p* = 0.005 values; so, the fourth hypothesis is also accepted. Technical attributes were positively related to adoption of seed management practices with beta 0.234 and *p* = 0.000 values; so, the fifth hypothesis is accepted. Finally, wheat productivity was positively related to adoption of seed management practices with beta 0.190 and *p* = 0.002 values, which led to the acceptance of the sixth hypothesis.

Hence, it is likely to be observed that technical attributes were the strongest drivers of seed management adoption, followed by informational access, financial considerations, and marketing parameters. These factors positively influenced farmers' adoption decisions, while institutional services showed no significant effect. Adoption of seed management practices, in turn, had a strong positive impact on wheat productivity.

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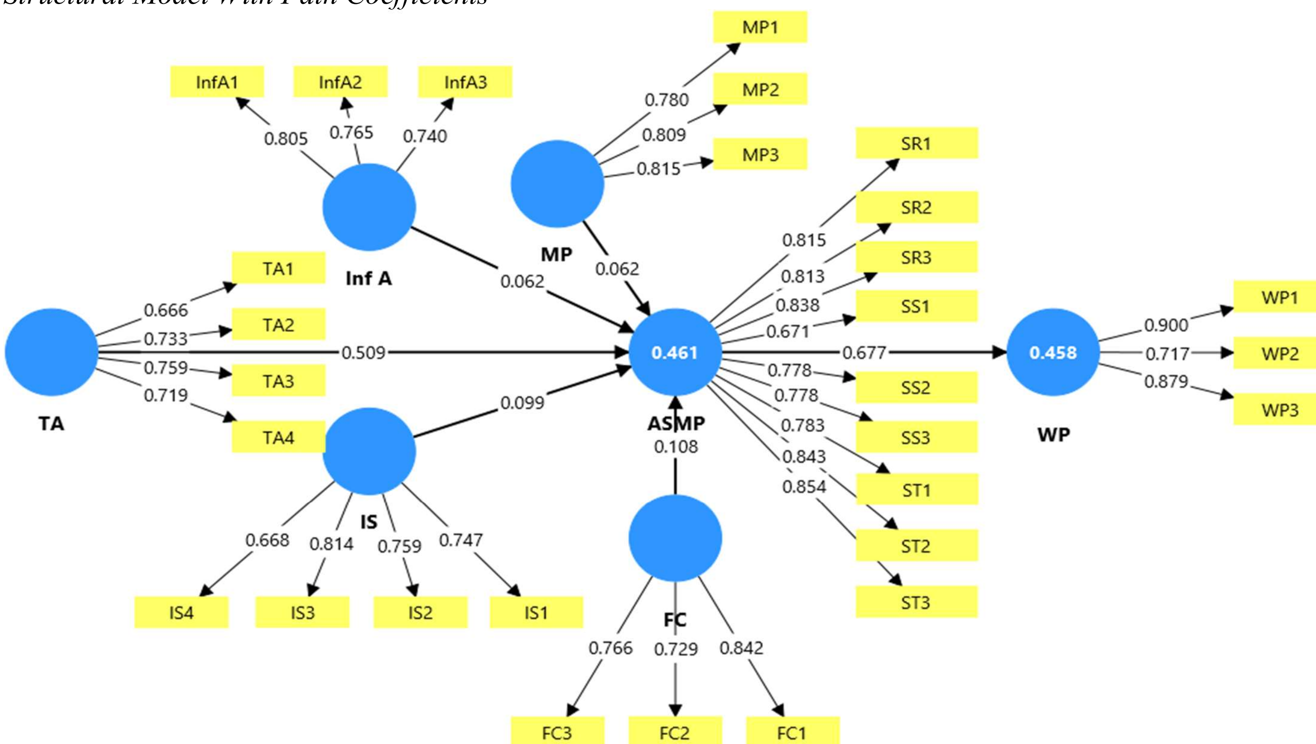
Table 8
Direct Relationships

Relationships	Std. Beta	Std. Dev.	*t* Value	*p* Values
FC → ASMP	0.159	0.060	2.502	0.005
InfA → ASMP	0.362	0.078	2.074	0.000
IS → ASMP	0.027	0.043	0.546	0.293
MP → ASMP	0.192	0.074	2.554	0.005
TA → ASMP	0.234	0.065	1.286	0.000
WP → ASMP	0.190	0.060	2.820	0.002

Note. ASMP = adoption of seed management practices; FC = financial consideration; InfA = information access; IS = institutional services; MP = marketing parameters; TA = technical attributes; WP = wheat productivity.

Figure 2
Structural Model With Path Coefficients



Note. The figure displays the PLS-SEM results, including item loadings, path coefficients, and R² values for adoption of seed management practices (ASMP) and wheat productivity (WP). Adapted from the study analysis.

6. Discussion, Implications, and Limitations

Awareness of modern farming practices is growing globally, prompting farmers to adopt improved seed management techniques for higher productivity. In Pakistan, efficient seed management proves vital for farm output and profitability. A key study found that determinants such as farmer awareness and adoption of extension-recommended wheat varieties, supported by seed treatment, timely replacement, and proper storage, are positively linked to better yields (Ullah et al., 2022). Understanding this relationship is essential for policymakers, extension agents, and input suppliers aiming to promote broader adoption and ultimately enhance wheat productivity across the region. The study also highlights that factors like education, farm size, and extension contact significantly influence farmers' awareness and adoption decisions. Additionally, the

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research emphasizes the importance of tailored interventions that consider the diverse socioeconomic characteristics of farmers to effectively promote sustainable agricultural practices (Jameel et al., 2023).

Technical attributes significantly influenced adoption (*b* = 0.234), indicating that farmers are more likely to adopt seed management practices when convinced that certified seeds, proper treatment, and modern storage enhance yields. Emphasizing cost-effectiveness, these attributes drive adoption by demonstrating clear benefits and minimizing risks. Farmers' willingness to invest in proven practices reflects their recognition of long-term gains. Supportive measures reinforcing these benefits foster internalized and sustained adoption. Extension campaigns promoting certified seeds, proper treatment, and scientific storage as essential to "right farming" can further boost adoption and improve wheat productivity. Moreover, technical training and field demonstrations can enhance farmers' confidence in these practices, while peer learning networks amplify awareness through community-based adoption. Integrating these technical attributes with financial incentives and access to inputs ensures broader and more equitable uptake across farming populations (Saeed et al., 2020).

While marketing parameters strongly influenced adoption of seed management practices (*b* = 0.192), the results show that farmers were more likely to adopt improved practices when they believed that current adoption would lead to future benefits such as higher yields and improved market opportunities (Zia et al., 2024). This perception further reinforced their commitment to consistently implementing these practices. Marketing-related factors such as access to reliable buyers, price information, and demand forecasts play a key role in shaping farmers' decisions, motivating them to maintain high-quality seed management practices to secure both productivity and market gains (Dadlani et al., 2023).

Financial considerations significantly influenced the adoption of seed management practices (*b* = 0.159), indicating that farmers are more likely to adopt improved practices when they can afford costs such as certified seeds, treatments, and proper storage. Limited access to credit and high input prices act as barriers, reducing adoption and negatively affecting wheat productivity. Strengthening financial support through affordable credit, subsidies, and cost-sharing mechanisms can encourage broader adoption, enabling farmers to implement modern seed management practices more consistently (Yu et al., 2024). Additionally, integrating financial literacy and planning into extension programs can help farmers make informed investment decisions, ensuring sustainable gains in productivity and profitability. Access to flexible loan schemes and cooperative financing can further mitigate financial constraints, particularly for smallholder farmers. Encouraging partnerships between banks, input suppliers, and agricultural extension services can streamline support and improve timely availability of resources. Ultimately, enhancing financial capacity empowers farmers to take calculated risks, adopt innovative practices, and achieve long-term improvements in wheat yield and farm income (Abate, 2024; Rayhan et al., 2023).

Informational access showed a significant positive effect on the adoption of seed management practices (*b* = 0.362). Farmers with timely access to agricultural information—such as recommended seed varieties, proper treatment methods, and optimal sowing techniques—are more likely to implement improved seed management practices. The availability of accurate and reliable information enhances farmers' confidence in adopting new practices, reduces uncertainty, and ultimately leads to higher wheat productivity (Luqman et al., 2024). Strengthening knowledge dissemination through extension services, digital platforms, and peer learning can therefore play a vital role in sustaining adoption and improving output. Furthermore, regular training programs and workshops can help farmers stay updated with innovations in seed management. Collaboration between government agencies and private input suppliers can ensure that information reaches even remote farming communities, fostering equitable adoption and improved regional yields (Ahmed et al., 2024).

Institutional services had a weak negative effect on the adoption of seed management practices (*b* = 0.027), indicating that existing support mechanisms such as subsidies, credit, and extension programs are often inadequate, poorly implemented, or inaccessible. Rather than facilitating adoption, these shortcomings discourage farmers from adopting improved practices, ultimately lowering productivity. Using a uni-dimensional measure of institutional support, the study demonstrates how weak systems reduce intrinsic motivation and limit the benefits of modern seed practices (Baglan et al., 2020). Strengthening institutional frameworks with timely, farmer-focused support is essential to enhance adoption and improve wheat yields. Additionally, coordinated efforts between government agencies and local cooperatives can help address accessibility gaps, while monitoring and feedback systems can ensure that institutional programs are responsive to farmers' evolving needs. Building trust in institutional support can further encourage consistent adoption of modern seed management practices (Hussain & Maharjan, 2025).

6.1 Theoretical Implications

This research contributes to the literature by positioning the adoption of seed management practices as the central determinant influencing wheat productivity, supported by five key first-order factors: technical attributes, marketing parameters, financial considerations, informational factors, and institutional services. The study demonstrates that technical knowledge, financial capacity, market access, and timely information positively drive adoption, whereas institutional inefficiencies act as barriers. Unlike prior studies that examined these factors separately, this research integrates them into a comprehensive, context-specific framework for Punjab, capturing how multiple socio-economic and structural factors collectively shape adoption behaviour (Bilal et al., 2024). Guided by the Diffusion of Innovations Theory, the findings reveal that adoption is influenced not only by rational considerations but also by behavioural and contextual factors such as information flow, institutional support, and perceived benefits, highlighting the multifaceted nature of technology uptake in agriculture. The results emphasize that coordinated interventions across these determinants are essential for maximizing adoption and productivity. Policymakers and extension agencies should focus on strengthening technical training, improving access to financial and market resources, and ensuring timely dissemination of information to farmers. Furthermore, addressing institutional gaps by making support programs more accessible and responsive can significantly enhance the sustainability of adoption. Integrating these strategies can help create an enabling environment where farmers are motivated and equipped to implement improved seed management practices consistently, ultimately boosting wheat yields and overall farm profitability in the region.

6.2 Practical Implications

Farmers and agricultural stakeholders in Pakistan are increasingly adopting improved seed management practices due to their potential to enhance wheat productivity. However, sustained adoption requires addressing key constraints and fostering intrinsic motivation among farmers. This study offers practical implications for policymakers, extension agents, and agribusiness firms. Findings highlight that intrinsic motivation is crucial; thus, awareness campaigns should integrate moral and community-oriented messages, linking farmers' responsibility for food security and sustainability with tangible benefits such as higher yields and reduced losses. Policymakers should emphasize long-term advantages, including improved soil health, resilience to climate variability, and profitability. Addressing institutional inefficiencies through timely input delivery, effective extension services, and transparent support mechanisms is essential. Simultaneously, improving access to credible information via digital tools, farmer field schools, and community networks can strengthen farmers' confidence in adopting these practices. Financial accessibility through targeted subsidies and low-interest credit can further encourage investment in improved seeds. Aligning marketing strategies, institutional support, and informational outreach with farmers' intrinsic motivation and perceived benefits can significantly enhance adoption, thereby increasing wheat productivity, boosting farm incomes, and contributing to national food security and agricultural sustainability.

6.3 Limitations and Future Research

This study provides valuable insights but has several limitations. It focused primarily on internal drivers of seed management adoption, technical, financial, informational, marketing, and institutional, while excluding external influences such as climate variability, policy shifts, and market fluctuations, which may also affect adoption behaviour. Adoption was examined as the primary outcome; future studies should evaluate its impact on actual wheat productivity across multiple cropping seasons to capture more nuanced effects. The cross-sectional design limits causal inference, highlighting the need for longitudinal studies to observe changes in adoption patterns over time. Additionally, data were drawn solely from wheat farmers in

Punjab, Pakistan; incorporating multiple provinces and diverse agro-ecological zones would improve the generalizability of the findings. Finally, future research could explore the interplay between internal and external factors, including socio-political and environmental constraints, to provide a more comprehensive understanding of adoption dynamics in wheat farming (Bilal & Jaghdani, 2024).

Furthermore, the reliance on self-reported data may introduce biases such as social desirability or recall errors, which can affect the accuracy of the findings. The study's focus on individual-level factors may overlook community-level influences and social networks that play a significant role in the adoption of seed management practices. The absence of a comparative analysis with non-adopters limits the ability to draw definitive conclusions about the effectiveness of the adoption strategies. Additionally, the study did not account for the temporal aspect of adoption, as practices and perceptions may evolve over time, influencing long-term adoption outcomes. The exclusion of gender and age as variables may overlook demographic influences on adoption behaviours. Lastly, the study did not assess the environmental sustainability of the adopted practices, which is crucial for evaluating the broader impacts of agricultural innovations (Sarfaraz & Javed, 2023).

7. Conclusion

Previous research on agricultural technology adoption has largely focused on rational-economic factors such as cost, perceived benefits, and resource availability. However, limited attention has been given to the multidimensional influences on adoption, particularly in seed management practices. This study fills this gap by examining the adoption of wheat seed management practices in Punjab, Pakistan, through five key determinants: technical knowledge, financial resources, marketing access, informational support, and institutional services. Results show that technical, financial, marketing, and informational factors positively drive adoption, whereas institutional services have a negative effect, reflecting inefficiencies and lack of trust in support systems. These findings highlight the need for farmer-focused extension services, reliable information access, and institutional reforms. By presenting an integrated adoption framework, this study moves beyond economic perspectives, emphasizing the combined roles of informational, infrastructural, and institutional dimensions. The insights offer guidance for policymakers and practitioners to design effective strategies for sustainable seed management, enhancing wheat productivity and food security.

Author Contributions

All authors participated in ideation, development, and writing the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

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Informed Consent

Informed consent was obtained from all participants prior to data collection. Participants were informed about the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without any consequences. The confidentiality and anonymity of respondents were guaranteed throughout the research process.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. The authors are committed to transparency and will provide detailed methodological information and analysis protocols upon request.

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