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Influence of Information Sources on Technology Adoption in Apple Production in China

Linjia Yao [1], Gang Zhao [2,3,*], Changqing Yan [4], Amit Kumar Srivastava [5,6], Qi Tian [1], Ning Jin [7], Junjie Qu [8], Ling Yin [8], Ning Yao [9], Heidi Webber [6], Eike Luedeling [10] and Qiang Yu [2,3,*]

[1] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China; linjia.yao@nwafu.edu.cn (L.Y.)
[2] College of Soil and Water Conservation Science and Engineering, Northwest A&F University, Yangling 712100, China
[3] State Key Laboratory of Soil and Water Conservation and Desertification Control, Northwest A&F University, Yangling 712100, China
[4] College of Intelligent Equipment, Shandong University of Science and Technology, Taian 271019, China
[5] Institute of Crop Science and Resource Conservation, University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany
[6] Leibniz-Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
[7] Department of Resources and Environmental Engineering, Shanxi Institute of Energy, Jinzhong 030600, China
[8] Guangxi Crop Genetic Improvement and Biotechnology Key Laboratory, Guangxi Academy of Agricultural Sciences, Nanning 530007, China
[9] College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, China
[10] Horticultural Sciences, Institute of Crop Science and Resource Conservation, University of Bonn, Auf dem Hügel 6, 53121 Bonn, Germany
* Correspondence: gang.zhao@nwafu.edu.cn (G.Z.); yuq@nwafu.edu.cn (Q.Y.)

Abstract

China holds the largest apple cultivation area globally, yet yields per hectare remain relatively low. Despite substantial government investment in modern orchard technologies, adoption remains limited among farmers. This study investigates the economic and sociological drivers of technology uptake, focusing on how information sources shape adoption behavior. Based on 382 farmer surveys across major apple-producing provinces, the study examines (1) farmers' preferences for agricultural information sources, (2) the influence of demographic characteristics on those preferences, and (3) the differential effects of specific sources on the adoption of key technologies, including dwarf rootstocks and virus-free seedlings. Results show that agri-chemical dealers (ACDs) and farmer peers (FPs) are the most commonly used information channels. Access to advice from local experts (EXPs) significantly increases the likelihood of adopting dwarf rootstocks, while information from ACDs promotes the use of virus-free seedlings. In contrast, reliance on personal farming experience is negatively associated with technology uptake. These findings highlight the need to strengthen formal information dissemination systems and better integrate trusted local actors like ACDs and EXPs into agricultural extension. Targeted information delivery can improve adoption efficiency, promote evidence-based decision-making, and support the modernization and sustainability of China's apple sector.

Keywords: apple production; technology adoption; agricultural extension; information networks; rural sociology

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1. Introduction

China is the world's leading producer and cultivator of apples (*Malus domestica*), accounting for over 50% of the global apple planting area [1]. As a key cash crop, apples play a pivotal role in China's rural economy—not only contributing significantly to agricultural export revenues but also serving as a critical income source for millions of smallholder farmers. The sector has been instrumental in supporting poverty alleviation and fostering economic self-sufficiency in rural regions [2,3]. Despite steady growth in per-unit yield and profitability over recent decades (Figure 1), China's apple productivity remains markedly lower than that of high-efficiency producers such as New Zealand, the United States, Italy, and Germany [1,4,5]. One of the key factors constraining further productivity gains is the continued reliance by many growers on traditional orchard systems, characterized by standard rootstocks, wide planting distances, and experience-based management. While rooted in long-standing agricultural practices, these systems often exhibit lower labor efficiency, reactive pest control, and suboptimal resource utilization under current ecological and market conditions [6–8]. In contrast, modern orchard systems—including high-density dwarf plantings, virus-free seedlings, integrated pest management (IPM), and certified organic farming—emphasizer precision management and improved input efficiency, aiming to enhance productivity, reduce production costs, and support long-term sustainability [9]. The slow transition toward knowledge-intensive orchard systems has broader implications for rural development and agricultural modernization. Without widespread adoption of advanced technologies and practices, the transformation of China's apple sector—and its contribution to rural revitalization strategies—remains limited.

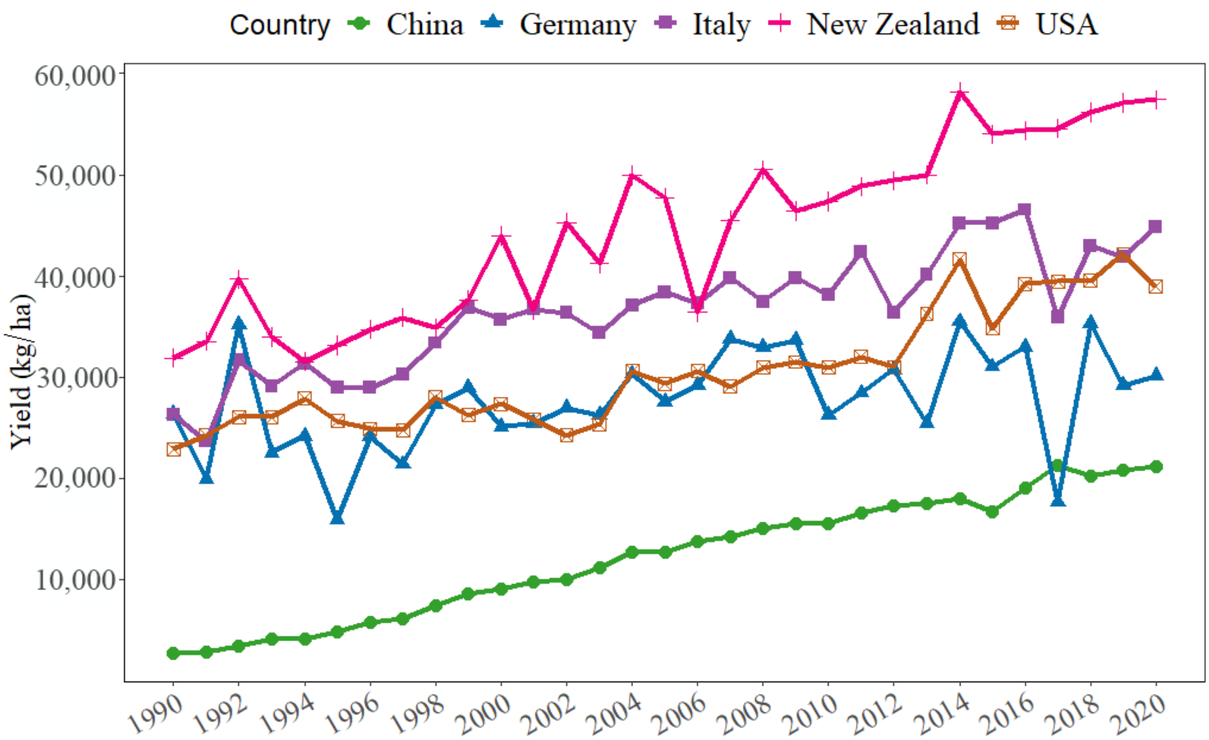

Figure 1. Apple yields in kg ha^{-1} (from 1990–2020) for major apple-producing countries. Source: https://www.fao.org/faostat/en/#home (accessed on 12 July 2021).

Among these, dwarf rootstock cultivation enables higher planting density and earlier fruiting, which can increase yields and accelerate the return on investment [10–12]. Virus-free seedlings, on the other hand, have been shown to significantly reduce disease incidence—such as from apple chlorotic leaf spot virus—offering better protection than reactive fungicide applications [13].

Although the agronomic and economic benefits of these innovations are well-documented [14], uptake among Chinese apple growers remains limited. One of the main constraints is the gap between scientific knowledge and farmers' perceptions; in particular, a lack of understanding regarding the operational and economic advantages of new technologies [15,16]. Compared with other leading apple-producing countries, the adoption rate in China is markedly lower [17–20]. This underscores the urgent need to improve the effectiveness of agricultural extension systems in disseminating credible and actionable information.

Empirical research increasingly recognizes that information is a key production input—alongside land, labor, capital, and management—that shapes farm-level decision-making [21]. Accurate, timely, and relevant agricultural information enhances farmers' ability to assess risks and make informed adoption choices [22]. In practice, farmers access such information through both formal and informal channels: direct contact with extension officers, agri-input dealers, peer networks, television, mobile apps, and more. These sources differ not only in credibility and reach but also in the type and quality of knowledge they convey, which, in turn, influences adoption behavior [15,23–25].

In China's "large country, small farmer" context—characterized by fragmented landholdings and heterogeneous grower profiles—information acquisition is shaped by demographic and farm characteristics such as age, education level, and orchard size [26,27]. As a result, individual farmers construct personalized information systems, which mediate their access to technology-related knowledge and their willingness to adopt innovations. Understanding these information preferences and their heterogeneity is critical to improving the design and targeting of extension services. However, empirical evidence on how different information sources affect technology-adoption decisions in the context of perennial horticultural crops remains sparse. This study aims to address this gap by focusing on the apple sector in China. The specific objectives are to

(1) Identify farmers' preferences for different agricultural information sources;
(2) Examine how demographic and orchard characteristics influence these preferences;
(3) Evaluate the impact of information source types on the adoption of key modern technologies; and
(4) Assess the potential contribution of these technologies to economic performance, as measured by gross margins (defined as revenue minus direct costs).

This study adopts a holistic perspective by examining the full pathway from information acquisition to economic outcomes. Understanding how different information sources shape adoption behavior is essential, but it is equally important to assess whether such adoption ultimately translates into tangible economic benefits. If the adoption of modern technologies leads to increased gross margins, this strengthens the rationale for improving farmers' access to reliable and effective information. Therefore, the fourth objective serves to reinforce the practical significance of information-driven adoption.

Based on the above objective, this study draws on farm-level data to analyze how farmers' access to various information sources influences the adoption of modern agricultural technologies, and whether such adoption leads to improved economic outcomes in apple production.

2. Literature Review

Agricultural technology adoption is a multifaceted process influenced by economic, social, and informational factors. Existing literature has drawn on decision theory and innovation diffusion theory to explain the determinants of adoption behavior [28]. Among the theoretical approaches, one of the most influential is the Diffusion of Innovation (DoI) theory proposed by Rogers [29], which offers a structured perspective on how new technologies are adopted by individuals within a social system.

According to Rogers, diffusion is "the process in which an innovation is communicated through certain channels over time among the members of a social system." This framework emphasizes four core components: the innovation itself, communication channels, time, and the social system [30]. Among these, communication channels—ranging from mass media to interpersonal sources—play a critical role in shaping individuals' knowledge, persuasion, and ultimate decisions regarding whether to adopt an innovation [30]. Rogers describes the adoption process as a five-stage sequence: knowledge, persuasion, decision, implementation, and confirmation. Throughout these stages, especially the earlier ones, individuals rely on information sources to reduce uncertainty and to evaluate the innovation's perceived attributes, including its relative advantage, compatibility, complexity, trialability, and observability [30].

In our study, we use this framework to examine how various information channels—specifically agri-chemical dealers, farmer peers, and local experts—affect the knowledge and persuasion stages of apple growers' decisions to adopt modern agricultural technologies such as virus-free seedlings and dwarf rootstocks. Rather than applying the full five-stage model, we focus on how exposure to different sources of information shapes farmers' perceptions of innovation characteristics, thereby influencing their likelihood of adoption. Building on this conceptual foundation, we now review the empirical literature on farmers' information source preferences and technology-adoption decisions.

The literature on this topic mainly focuses on three aspects: (1) how personal characteristics influence preferences for information sources; (2) how different information sources affect technology-adoption decisions; and (3) to what extent the adoption of new technologies affects returns.

The preference for information sources is influenced by farmers' demographic backgrounds (e.g., education level, farm size, and diversity of agricultural production) and orchard characteristics [31,32]. A survey conducted in Pakistan found significant differences in information sources preferences between men and women [33]. A study in India pointed out that a farmer's education, income, and social class are important sociodemographic factors affecting the adoption of information sources when obtaining information on various agricultural practices [34]. A study in India showed that farmers with irrigated land tended to favor advice from mass media, while farmers with rainfed lands favored advice from government agencies [35]. Poultry farmers in Tanzania preferred interpersonal and informal information sources because they provided quick access and immediate feedback [36]. Moreover, some previous studies have reported that farm size was a principal factor that influenced farmers' preference for information sources [37,38].

How preferences for information sources affect farmers' behavior has been well documented in previous studies from other countries [23,39–43]. For example, farmers actively seek or passively receive different information from information sources to make a range of management decisions during the apple growing season [23,44,45]. A study in the USA showed that as an information source, the private sector had the greatest impact on farmers' decisions regarding nitrogen management [46]. In southern Africa, farmers' access to credit and agricultural extension services was positively impacted by the adoption of climate-smart agricultural technologies [47]. Similarly, in underdeveloped countries such as Uganda, farmers having a higher level of information access from various channels used more inputs such as pesticides and fertilizer [48].

Information regarding technology and management practices from various information sources could have an impact on farming outcomes. For example, in Ethiopia, the advice provided by extension agents had a positive impact on both crop yields and income [49]. In Zimbabwe, extension services provided information to farmers about drought-tolerant maize and increased maize production per capita [40]. Similarly, using information about fertilizer recommendations increased maize productivity and profits in Ethiopia [39]. A study in India found that when farmers gathered information from at least one formal channel, there was a significant positive impact on cotton yield and quality [35]. Another study indicated that cooperatives can significantly increase growers' agricultural benefits by providing agronomic advice together with physical products [50].

A substantial body of relevant literature has presented a robust theoretical foundation for our exploration of this topic. Nevertheless, there remains a lack of direct studies examining the information source preferences of apple growers and the diverse effects on their decision-making. In light of this gap, the objective of this paper is to investigate a model for the targeted promotion of modern agricultural technologies to small-scale growers. This involves analyzing the information source preferences of diverse farmers, disseminating high-quality practical information, and thereby enhancing the efficiency of their decision-making regarding technology adoption.

3. Materials and Methods

3.1. Study Area

Apple is cultivated in most provinces in China except for six southern provinces due to climatic constraints (Figure 2a). According to previous studies [8], seven major apple-producing provinces in China—Shaanxi, Shandong, Gansu, Henan, Shanxi, Hebei, and Liaoning—account for over 90% of the country's total apple production. In this study, we selected seven provinces—Shaanxi, Shandong, Gansu, Shanxi, Liaoning, Henan, and Xinjiang—replacing Hebei with Xinjiang due to data availability and its growing importance in apple production (Figure 2d). In 2019, Shaanxi province had the largest planting area and highest production output (Figure 2a,b), while Shandong province recorded the highest average yield (Figure 2c). Shanxi and Gansu provinces also showed notable production volumes and yields. Together, these seven provinces accounted for 80.2% of the national apple planting area and 86.6% of the total production output in 2019 [51], ensuring the representativeness of our sample in terms of geographic distribution and production scale.

3.2. Preference in Information Sources

Preference in information sources here refers to a farmer's behavior and attitude toward various information sources with regard to managing their orchards to achieve their economic goals [52]. When farmers make a management decision, they often rely on one or more channels of information. In China, seven commonly used information sources are available to apple growers, including agri-chemical dealers (ACDs), agricultural technology extension services (ATESCs), local experts (EXPs), farmer cooperatives (FCs), farmer peers (FPs), mass media (MM), and personal experience (PE) (Table 1). All these types of channels can, in principle, be useful to government agencies and agribusinesses for promoting the use of new agricultural technologies [53]. However, as shown in Table 1, the quality and availability of these information sources varies depending on the information owner and the regional coverage. If, and how, farmers make use of these types of information for their decision-making may impact their apple production and economic returns.

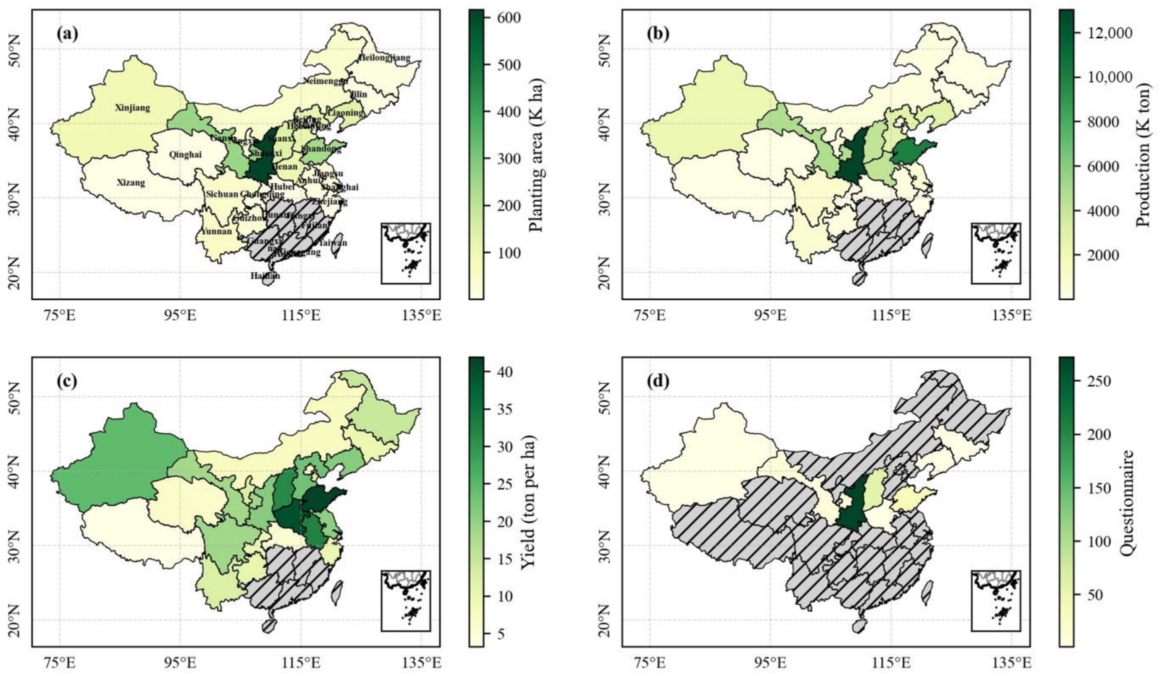

Figure 2. Planting area (**a**), production (**b**), yield (**c**), and number of questionnaires collected (**d**) for provinces in China. The unpainted areas in panels (**a**–**c**) indicate no apple production. The unpainted areas in (**d**) indicate that no questionnaires were collected. The data for (**a**–**c**) were from official statistical data for 2019. Source: http://www.stats.gov.cn/ (accessed on 12 July 2021).

Table 1. Different information sources that are commonly used by smallholder apple growers.

Information Source	Abbreviation	Quality	Availability	Description
Agri-chemical dealers	ACDs	Uneven	Widely available	Dealers normally have a store in the village to sell agricultural inputs such as seeds, fertilizer, and pesticides. They often give agronomic advice during sales efforts.
Agricultural technology extension service centers	ATESCs	Good	Varies across regions	These are official government agencies whose responsibility is to promote new agricultural technologies and varieties to farmers in towns and villages.
Local experts	EXPs	Good	Rarely available	Experts are normally trained and well-educated local farmers who have great knowledge of various orchard practices.
Farmer cooperatives	FCs	Good	Varies due to accessibility	Non-governmental organizations have a special team that is responsible for establishing linkages between farmer cooperatives and supermarkets.
Farmer peers	FPs	Uneven	Widely available	Friends, neighbors, and partners associated with farmers.
Mass media	MM	Uneven	Varies due to access availability	Radio, television, newspapers, and mobile phones.
Personal experience	PE	Uneven	Widely available	Farmers summarize their rules and experience gained through farming practice.

Source: Authors' own elaboration.

3.3. Management Decisions During the Growing Season

A range of decisions are made during orchard preparation (rootstock, seedling treatments), apple growing season (pesticide use, fertilization, fruit bagging), and post-harvest orchard maintenance. During the orchard preparation period, farmers need to decide on cultivation practices based on the local climate, soil, asset level, production systems, etc. Over the long-term, these practices will impact the apple price, pest/disease susceptibility, and yield. Farmers' decisions regarding the use of virus-free seedlings will later influence pesticide use intensity for disease control. During the apple growing season, farmers will make decisions regarding pesticide use and fertilization, including product type, application time, and amount to use to target specific insects and diseases, all of which will impact the final apple quality and tree health. For fruit bagging, farmers need to decide on the number of bags, kind of bag, etc. These decisions will impact fruit color and health. The frequency of these decisions varies during the apple growing season from orchard preparation to harvest. For example, pesticide use is relevant for almost the entire growing season, while rootstock choice only occurs during the orchard establishment stage. All these decisions, made seasonally and over the long-term, together determine apple tree health, apple production and quality, and profitability.

3.4. Questionnaire Design

To determine farmer attitudes toward new technology and different information sources regarding managing apple orchards, we designed a questionnaire survey that was sent to farmers across major apple production regions in China (Figure 2d). A summary of the questionnaire structure is provided in Table 2. The questionnaire design and implementation followed the best practice recommended [54]. The survey was digitized in a WeChat survey format that made implementation easy and structured [55].

The survey questions included four sections: demographic background, orchard characteristics, information usage and management decisions, agronomic inputs, and economic returns (Table 2). For the demographic background section, we collected variables related to famers' age, education, planting area, and agricultural cooperative membership status. In the orchard characteristics section, information such as the orchard size, apple tree variety, tree age, and tree planting pattern was collected. In the section on information use and management decisions, we collected data regarding farmers' options for seeking information from various channels for different management decisions. Questions related to preferences of information sources consisted of two kinds of questions related to product choices and application methods. The questions related to product choice looked like the following: "Which information source (s) do you use when you decide on which fungicide product to use?". A second question following the first one was "Which information source (s) do you refer to when you decide on the dosage and application timing?". Because we wanted to encourage respondents to respond to all the questions related to the information sources used, these questions were constructed with multiple-choice responses. The data used for analysis were the information sources that supported the first question rather than the second question. In the final section, data regarding agronomic inputs for the different management decisions and economic returns of the orchard were gathered. In this study, the economic return is defined as the average income per unit area, as answered by the farmers, and we calculated the total income based on the total area provided by the farmers. Then, we used the gross margin (GM) to measure differences in the orchard economic returns. In this study, costs only included management inputs such as pesticides, fertilizers, and fruit bags rather than the entire costs, which would have included land rent, seeding costs, etc. Consideration of the GM allowed for the determination of the relative outcomes of management decisions.

Table 2. Descriptive statistics for farmer and orchard characteristics included in the survey questionnaire.

Category	Variable	Variable Type	Question No.	Abbreviation	Description
Farmers' demographic background	Gender	Male/Female	2	GE	Gender of respondent
	Age	Integer	3	AG	Age of respondent
	Education level	Integer	4	EDU	Number of years of formal schooling
	Training	Binary (Yes/No)	10	TRA	Had the farmer participated in apple growing training?
	Identity	Binary (Yes/No)	14	ID	Was the responding person a full-time apple farmer?
	Farmer cooperative	Binary (Yes/No)	15	WFC	Had the farmer joined a farmer cooperative?
Orchard characteristics	Planting area	Measurement unit (mu)	8	AR	Area of apple orchard
	Tree age	Integer	12	TAG	Age of apple trees
Information choice and management decisions	Disease	Integer	30		Source of agronomic information and the number of disease species found in the orchard
	Insect pest	Integer	31		Source of agronomic information and the number of insect species found in the orchard
	Pesticide use	Integer	34		Source of agronomic information and the number of pesticides used in the growing season
	Fertilizer use	Integer	56		Source of agronomic information and the number of fertilizer applications in the growing season
Agronomic inputs	Pesticide cost	Integer (CNY/mu)	48		Cost of pesticides for the unit area over the entire growing season
	Fertilizer cost	Integer (CNY/mu)	58		Cost of fertilizers for the unit area over the entire growing season
	Fruit bag cost	Integer (CNY/mu)	61		Cost of fruit bags for the unit area over the entire growing season
Economic index	Economic returns	Integer (CNY/mu)	88		Economic returns for the unit area
	Gross margin	Integer (CNY/year)	Via calculation		The gross margin of the apple orchard per year

Source: Authors' own elaboration.

3.5. Survey Implementation

The survey was conducted through a combination of face-to-face interviews and online questionnaire tools [55]. A total of 30 enumerators—members of an apple-growers' WeChat group established by Northwest A&F University in 2021—were trained by researchers prior to the survey to avoid influencing respondents and to ensure consistent data collection procedures. These enumerators conducted interviews in person or by phone, assisting farmers in completing the questionnaire using the WeChat Mini Program "Wen Juan Xing," which provided a standardized, error-reducing data entry interface.

To enhance the representativeness and data quality, we employed a typical sampling strategy, which integrated both statistical data and expert-informed judgments. In the first stage, seven major apple-producing provinces—Shaanxi, Shandong, Gansu, Shanxi, Liaoning, Henan, and Xinjiang—were selected based on their combined share of over 80%

of the national planting area and 86.6% of the apple production output in 2019 [51]. In the second stage, within these provinces, representative counties and villages were chosen based on the advice of industry experts, as part of the purposive sampling approach. Then, within those areas, apple growers were randomly selected for interviews, provided they met the eligibility criteria.

A total of 382 valid questionnaires were retained after applying a set of quality-control filters, which included, but were not limited to the following: the grower's age had to be under 85; the survey duration had to exceed 5 min; the planting density was required to fall within a reasonable range (50–150 trees per mu); and the number of fungicide treatments had to be greater than zero. These procedures helped minimize sample bias, reduce recall errors, and ensure data validity. The share of completed questionnaires from each province roughly corresponded to their respective planting areas, which explains the relatively higher sample share from Shaanxi province.

Each interview took approximately 30–60 min, and respondents received a small financial incentive (CNY 30 ≅ USD 4.2) for their participation.

3.6. Data Analysis

The study employed both descriptive and inferential statistical approaches to clarify the relationships among the characteristics of farmers and orchards, new-technology adoption, farmers' preference for information sources, orchard performance, and economic returns.

For the descriptive statistical analysis, we first summarized the characteristics of the respondents and their orchards. We grouped and counted the use of different information sources during the decision-making process during orchard preparation and during in- and post-season orchard management. To determine the factors affecting farmers' preference for information sources, we used a binary logistic regression between the demographic background and orchard characteristics with the choice of information sources [56]. We set the farmer demographics and orchard characteristics as the independent variables and the choice of information sources as the dependent variable. Given that the dependent variable was dichotomous, we used the following binary logistic model through the Python (V 3.12.7) package of statistics models [57]:

$$Ln[P_i/(1-P_i)] = \beta_0 + \sum_{j=1}^{\infty} \beta_j X_j + \varepsilon_i \tag{1}$$

where P_i is the probability of the various information source choices of individual i; X_j is the influencing factor j; β_0 is a constant term representing the intercept; β_j is the regression coefficient of X_j; and ε is a mean-zero stochastic term.

Then, to determine the impact of information sources on new-technology adoption, we used the same method to analyze this effect. We treated this as a dichotomous problem [58–60]. The choice of information sources was the independent variable, and the adoption of technology was the dependent variable. On the other hand, farmers' attitudes toward new technologies are often influenced by demographic, social–economic, and business-related factors [29,61]. The impact of farmer and orchard characteristics on technology adoption was considered in the data analysis, which added control variables into the model to increase the reliability of the results [19].

$$\begin{aligned} Y_i = \alpha + \beta_1 ACD + \beta_2 ATESC + \beta_3 EXP + \beta_4 FC + \beta_5 FP + \beta_6 MM + \beta_7 PE + \beta_8 GE + \beta_9 AG + \beta_{10} EDU + \beta_{11} AR \\ + \beta_{12} TRA + \beta_{13} TAG + \beta_{14} ID + \beta_{15} WFC + \varepsilon_i \end{aligned} \tag{2}$$

where Y_i refers to whether the farmer adopted the two new technologies. The coefficients β_1 through to β_{15} indicate the coefficient of each independent variable [62]. GE, AG, EDU, AR, TRA, TAG, ID, and WFC are farmer and orchard characteristics that are defined in Table 2. ε is a mean-zero stochastic term. The coefficient of independent variables in the Results section is referred to as the B-value. The sign of the B-value indicates the positive or negative impact of corresponding variables on the dependent variables. The Odds Ratio (OR) indicates the probability of whether a dependent variable (e.g., whether a technology was adopted) changed in response to an independent variable (whether an information source was chosen).

For the analysis of the impact of technology adoption on orchard health, productivity, and profitability, we used inferential statistics. We first compared the average values of GM, the number of disease/insect species, and the pesticide/fertilizer application frequency. Then we used the Student's *t*-test to test whether there was a significant difference between these two groups of sample means. The *t*-test was conducted with SciPy.Stats package in Python (V 3.12.7) [63].

3.7. Variable Definition and Measurement

To enhance the reliability of the analysis, the key variables in this study were defined as follows:

- Technology adoption was measured using two binary variables: whether the farmer adopted virus-free seedlings and whether they adopted the densely planted dwarfing system. A value of 1 indicates adoption, and 0 indicates non-adoption.
- Information source use was collected via a multiple-choice question, allowing farmers to select more than one source. For each information source—including agri-chemical dealers, agricultural technology extension service centers, local experts, farmer cooperatives, farmer peers, mass media and personal experience—a separate binary variable was created (1 = used, 0 = not used).
- Orchard output was measured using the average selling price (CNY/kg) and average commercial fruit revenue per mu (where 1 hectare = 15 mu), both based on farmer-reported data.
- Pest and disease pressure was quantified as the number of distinct pest or disease types reported by each farmer.
- Input use frequency referred to the average number of pesticide and fertilizer applications per mu per year, based on growers' responses.
- Production costs were limited to annual variable costs, including expenses on pesticides (average annual input per mu, using the midpoint of reported ranges), fertilizers (same as above), irrigation, fruit bags, and labor for bagging and unbagging. Fixed costs such as land rent and total labor expenses were not included.

All variables were collected through a structured questionnaire with standardized definitions and consistent units, ensuring comparability across respondents.

4. Results

4.1. Demographic and Orchard Characteristics of Respondents

The survey captured a diverse sample of apple growers across major production regions in China. Key demographic and farm-level characteristics are summarized in Figure 3. The majority of respondents were aged between 40 and 65 years (Figure 3a), reflecting the aging profile of the agricultural labor force in perennial crop sectors. Male farmers accounted for approximately two-thirds of the respondents (Figure 3b), consistent with gender patterns in agricultural land and labor management. Most farmers reported not having received formal agronomic training (Figure 3c), and the majority had not joined a farmers' cooperative (Figure 3i), indicating low engagement with institutional support structures. Approximately 60% of respondents were full-time farmers, while the remaining 40% identified as part-time growers (Figure 3d). Notably, nearly half of the surveyed farmers had not adopted dwarf rootstock systems, despite their widespread promotion by agricultural authorities (Figure 3e).

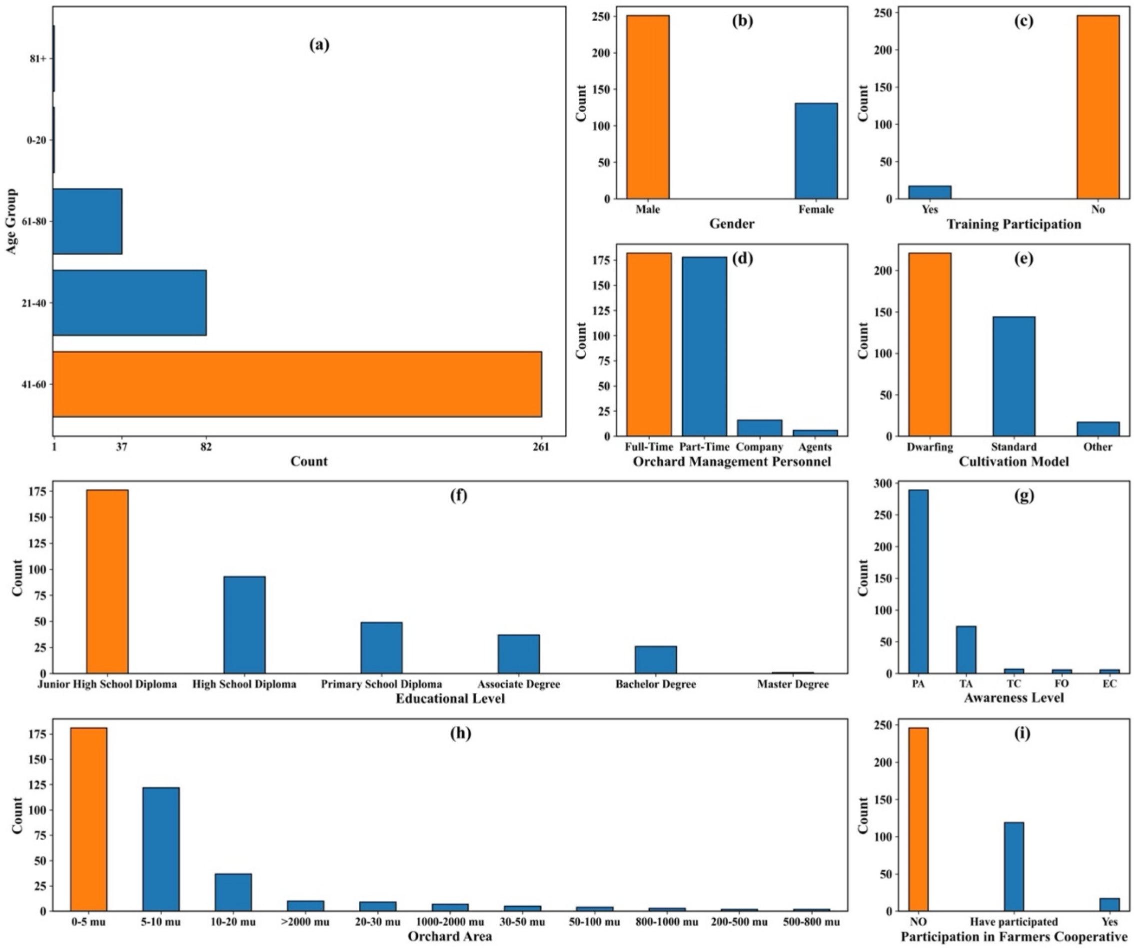

Figure 3. Summary of participants' demographic backgrounds. (**a**) Age; (**b**) Gender; (**c**) Training Participation; (**d**) Orchard Management Personal (full-time or part-time); (**e**) Cultivation Model; (**f**) Education Level; (**g**) Awareness Level, PA is "Behavior of Preventive Fungicide Application", TA is "Lacking Preventive Fungicide Application Behavior, Only Treating Pests and Diseases Once They Manifest", TC is "Possessing the Awareness of Preventive Fungicide Application but Lacking the Time to Implement it", FO is "Following Others Pest and Disease Control Strategies", EC is "Possessing the Awareness of Preventive Fungicide Application but Lacking Economic Capacity". (**h**) Orchard Area; (**i**) Participation in Farmer Cooperative. Source: Own calculations.

Education levels among respondents were generally low, with the majority having not completed high school (Figure 3f), which may constrain access to and comprehension of technical information. However, more than 80% of farmers self-reported a good understanding of pesticide application practices (Figure 3g), suggesting that practical knowledge may be acquired through experiential learning or informal channels. Regarding farm size, over 80% of respondents managed orchards smaller than 2 hectares (Figure 3h), reflecting the smallholder-dominated structure of apple production in China. This fragmentation has implications for the scalability of modern technologies and for the design of tailored extension programs. Figure 3g also provides insight into farmers' fungicide application behaviors. While some farmers practiced preventive spraying (PA), others only applied pesticides reactively (TA), lacked the time to implement preventive strategies (TC), followed neighbors' practices (FO), or were constrained by economic limitations (EC). These behavioral patterns highlight the variability in pest and disease management strategies, which are shaped by knowledge, capacity, and risk perception.

4.2. Farmers' Preferences of Information Sources

The survey results revealed clear variations in farmers' preferences for agricultural information sources, both overall and across specific management decisions (Figure 4). When aggregating responses across five core orchard management areas—rootstock selection, seedling treatment, pesticide application, fertilization, and fruit bagging—agri-chemical dealers (ACDs) emerged as the most frequently consulted source. Farmer peers (FPs) and local experts (EXPs) ranked second and third, respectively. In contrast, farmer cooperatives (FCs), mass media (MM), and agricultural technology extension service centers (ATESCs) were the least-used sources overall.

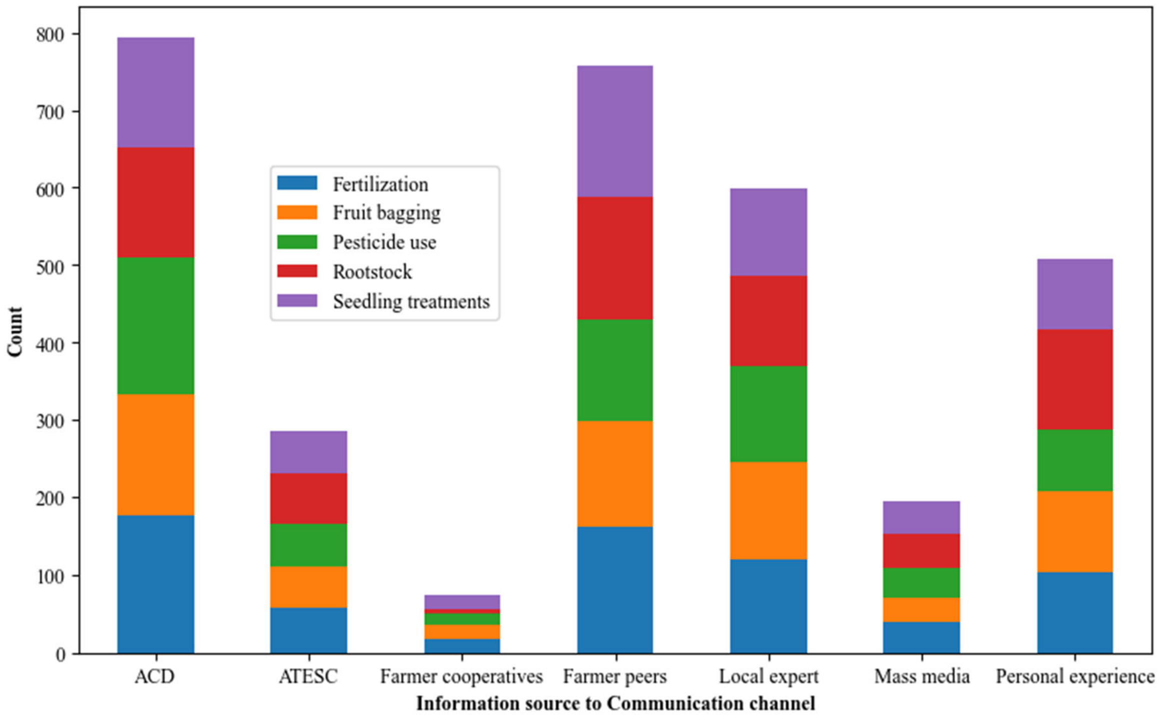

Figure 4. Preferred information sources for key management decisions related to apple production. Information sources included agri-chemical dealers (ACDs) and agricultural technology extension service centers (ATESCs). The *y*-axis indicates the number of growers using the corresponding information to make management decisions. Source: Own calculations.

Preferences varied depending on the management decision under consideration. For decisions related to rootstock and seedling treatment, farmer peers were the most commonly cited source, suggesting that experiential knowledge exchange plays a critical role in early-stage planting decisions. Conversely, for pesticide use, fertilization, and fruit bagging, ACDs were the primary information source, likely reflecting their direct involvement in input sales and advisory services. Notably, farmer cooperatives were the least-preferred information source across all five decision categories, reinforcing earlier findings on their limited functional role in current agricultural advisory systems. Similarly, mass media was not the top preference for any management decision, underscoring persistent barriers in digital information uptake among the surveyed population.

The number of information sources consulted by farmers varied significantly across different orchard management decisions (Figure 5). Approximately 50% of respondents relied on two distinct sources of information when making decisions across all five key management areas. A notable proportion—around 25%—depended on a single source when making decisions related to rootstock selection, fruit bagging, pesticide use, and seedling treatment. Fertilizer-related decisions showed slightly broader information use, with only 16.4% of farmers relying solely on one source. Use of multiple information channels beyond two was relatively rare. Only 3% to 5% of farmers reported using four or more sources to guide their management practices. This limited diversity in information sourcing may constrain farmers' exposure to complementary or higher-quality insights, potentially reducing the likelihood of informed and optimal decision-making.

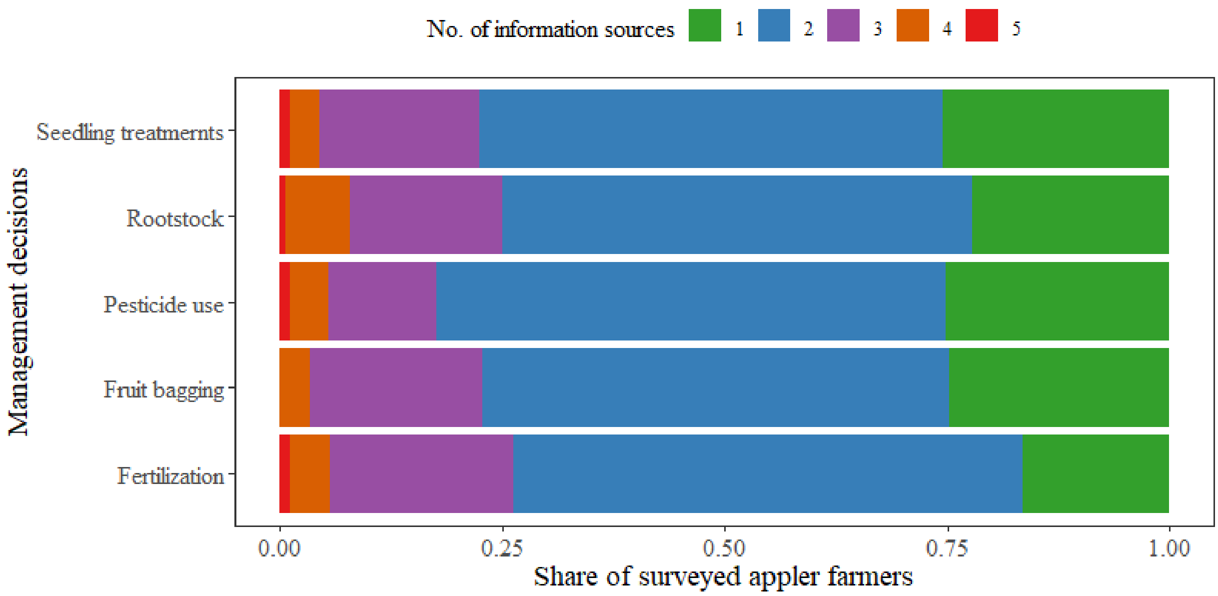

Figure 5. Number of information sources used in different management decision-making processes. Source: Own calculations.

4.3. Factors Affecting Farmers' Preferences of Information Sources

Regression results indicate that farmers' demographic and orchard characteristics significantly shaped their choice of information sources (Table 3). Female farmers were more likely to rely on farmer peers (FPs) but less likely to consult farmer cooperatives (FCs) or mass media (MM). Older farmers preferred agri-chemical dealers (ACDs) over experts (EXPs) or personal experience (PE), while more educated farmers favored ACDs and FCs, in contrast to less-educated farmers, who leaned toward EXPs and PE. Larger-scale farmers were more likely to consult agricultural technology extension service centers (ATESCs), whereas smaller-scale farmers tended to rely on their own experience. Participation in agricultural training and employment status also played key roles. Farmers without training were significantly more likely to depend on ACDs and FPs, while part-time farmers showed a strong preference for FPs and avoided EXPs and MM. Non-members of cooperatives relied more on ACDs and were less likely to use EXPs, FCs, or PE. These findings highlight the importance of tailoring extension strategies to farmer profiles and enhancing access to diverse, trusted information channels to promote informed decision-making and technology adoption.

Table 3. The influence of farmer background and orchard characteristics on the preference for information source. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; figures in parentheses are the Odds Ratios (ORs). Information sources include agri-chemical dealers (ACDs), agricultural technology extension service centers (ATESCs), local experts (EXPs), farmer cooperatives (FCs), farmer peers (FPs), mass media (MM), and personal experience (PE). Other information sources are not shown here because no significant relationships were found.

Variables	ACD	ATESC	EXP	FC	FP	MM	PE
Gender				−0.760 * (0.468)	0.562 * (1.753)	−0.940 *** (0.391)	
Age	0.061 *** (1.063)		−0.059 *** (0.943)				−0.034 ** (0.967)
Education	0.151 *** (1.163)		−0.144 ** (0.866)	0.148 ** (1.160)			−0.190 *** (0.827)
Planting area		0.002 ** (1.002)					−0.002 ** (0.998)
Training	1.025 *** (2.786)	−0.943 *** (1.364)	−0.824 ** (0.439)		1.155 *** (3.173)		
Tree age	0.122 ** (1.129)			−0.138 * (0.871)		−0.096 * (0.909)	
Part-time/Full-time			−0.629 ** (0.533)		1.037 *** (2.821)	−0.774 ** (0.461)	
Farmer cooperative	1.071 *** (2.920)		−1.574 *** (0.207)	−0.772 ** (0.462)			−0.768 ** (0.464)

Source: Own calculations.

4.4. Influence of Information Source on the Farmers' Adoption of New Technologies

Regression results indicate that the impact of information sources on technology adoption is technology-specific (Figures 6 and 7). For dwarf rootstock cultivation, local experts (EXPs) were the only source with a statistically significant positive influence. Farmers who obtained information from EXPs were 82% more likely to adopt dwarf rootstocks compared with those who did not (Odds Ratio = 1.82; $p < 0.05$). No significant effects were observed for other sources, suggesting that adoption of more technically demanding innovations is highly dependent on access to professional, expert-led guidance.

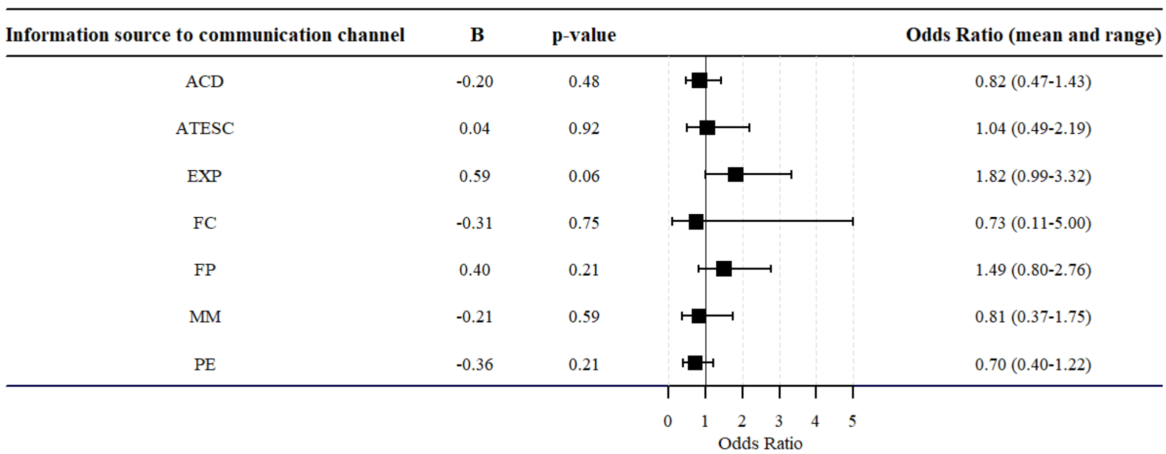

Figure 6. Role of information source on farmers' adoption of dwarf rootstocks. The sign for B indicates the direction of impact of the corresponding variable on the dependent variable, such as positive or negative (−). The Odds Ratio indicates the probability of a farmer adopting dwarf rootstock when using a specific information source compared with not using the specific information source. Odds Ratio ranges reflect uncertainty in the analysis. Source: Own calculations.

Information source to communication channel	B	p-value	Odds Ratio (mean and range)
ACD	1.50	0.00	4.47 (2.35-8.49)
ATESC	-0.07	0.86	0.93 (0.42-2.05)
EXP	0.07	0.85	1.07 (0.53-2.14)
FC	0.27	0.66	1.31 (0.40-4.33)
FP	0.14	0.67	1.15 (0.61-2.17)
MM	0.60	0.13	1.83 (0.83-4.01)
PE	-0.95	0.01	0.39 (0.20-0.768)

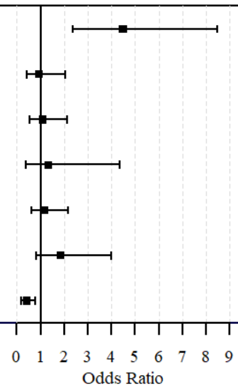

Figure 7. Role of information sources on farmer adoption of virus-free seedlings. The sign for B indicates the direction of impact of corresponding variables on the dependent variables, such as positive or negative (−). The Odds Ratio (OR) indicates the probability of a farmer adopting virus-free seedlings when using a specific information source compared with not using the specific information source. Odds Ratio ranges reflect uncertainty in the analysis. Source: Own calculations.

In the case of virus-free seedlings, two sources had statistically significant effects. Agri-chemical dealers (ACDs) had a strong positive influence on adoption: farmers consulting ACDs were 4.47 times more likely to adopt virus-free seedlings than those who did not (Odds Ratio = 4.47; $p < 0.01$). In contrast, reliance on personal experience (PE) was associated with a significantly lower likelihood of adoption (Odds Ratio = 0.39), suggesting that informal, self-guided decision-making may hinder the uptake of scientifically validated practices. These results emphasize the importance of aligning dissemination efforts with trusted and technically competent information providers to promote evidence-based adoption decisions.

4.5. Impact of Modern Agricultural Technology Adoption on Orchard Performance

Survey data revealed varying levels of adoption of modern agricultural technologies among apple farmers. Approximately 58.5% of respondents ($n = 181$) had adopted dwarf rootstock systems, while only 32.5% ($n = 101$) had adopted virus-free seedlings (Table 4). The results also showed that adopters of virus-free seedlings had slightly higher gross margins than non-adopters (mean = 82% for adopters versus 79% for non-adopters; $p < 0.1$), but adoption of dwarf rootstocks did not have clear benefits in terms of gross margins (Table 4). The average number of pesticide applications was significantly lower for farmers who adopted dwarf rootstocks (6.05 versus 6.81; $p < 0.01$) and for those who adopted virus-free seedlings (5.81 versus 6.61; $p < 0.01$). Clear benefits regarding disease occurrence were also found for the adoption of virus-free apple tree seedlings (mean = 2.09 versus 2.73; $p < 0.01$). Farmers who adopted these two new technologies experienced significantly lower numbers of pest species on their apple trees than non-adopters (mean = 1.77 versus 2.41; $p < 0.01$ and mean = 1.31 versus 2.39; $p < 0.01$, respectively). The average number of pesticide applications for farmers who adopted dwarf rootstocks and virus-free seedlings was significantly lower than for non-adopters. (6.05 versus 6.81 and 5.85 versus 6.61, respectively; $p < 0.01$). Interestingly, adoption of either technology was associated with increased fertilizer use, with adopters applying fertilizers more frequently than non-adopters (3.92 vs. 3.47 applications for dwarf rootstocks, and 4.34 vs. 3.45 for virus-free seedlings; $p < 0.01$). This may reflect heightened agronomic management intensity among adopters, potentially driven by efforts to optimize yield potential under improved cultivation systems.

Table 4. Differences in the gross margin and management intensity between adopters of new technology and non-adopters. The numbers (in parentheses) of adopters and non-adopters indicate the number and percentage of responses among the surveyed growers.

	Dwarf Rootstock				Virus-Free Seedlings			
	Adopters (181, 58.5%)	**Non-Adopters (129, 41.5%)**	***p*-Value**	**Cohen's d**	**Adopters (101, 32.5%)**	**Non-Adopters (210, 67.5%)**	***p*-Value**	**Cohen's d**
Gross margin	81%	79%	Not significant	0.144	82%	79%	$p < 0.1$	0.192
Number of disease species	2.33	2.80	$p < 0.01$	−0.357	2.09	2.73	$p < 0.01$	−0.496
Number of insect species	1.77	2.41	$p < 0.01$	−0.590	1.31	2.39	$p < 0.01$	−1.065
Number of pesticides used	6.05	6.81	$p < 0.01$	−0.381	5.85	6.61	$p < 0.01$	−0.379
Number of fertilizers used	3.92	3.47	$p < 0.05$	0.272	4.34	3.45	$p < 0.01$	0.550

Source: Own calculations.

The results of Cohen's d effect-size calculations show relatively large effect sizes ($|d| > 0.5$) for the number of disease and pest species, whereas economic indicators such as gross margin have smaller effect sizes, indicating more limited differences between the two groups.

5. Discussion

5.1. Differences in Preference for Information Sources and Their Implications

The study found clear heterogeneity in farmers' preference for agricultural information source (Figure 4), with agri-chemical dealers (ACDs) emerging as the dominant source across most decision contexts. This finding is consistent with prior studies [64] and reflects the widespread presence of ACDs in rural China. Often operated by local residents, these dealers maintain close relationships with farmers and frequently receive technical training from input suppliers, enabling them to offer production advice alongside product sales. In addition, local ACDs are often highly familiar with regional climate and production conditions, which further enhances their perceived relevance among farmers. This dual role—combining advisory and commercial functions—makes ACDs highly motivated to disseminate agronomic knowledge. However, as input retailers who also provide agronomic advice, ACDs are driven by commercial incentives, which may introduce potential risks. Even when correctly diagnosing the issue, they might still recommend higher dosages or a greater variety of agrochemical products, thereby contributing to the overuse of inputs such as fungicides and fertilizers [65,66]. Moreover, the quality and accuracy of advice vary substantially across dealers depending on their training and technical capacity.

In contrast, farmer cooperatives (FCs) were the least utilized information source. This aligns with earlier research highlighting structural and institutional barriers—such as weak governance, limited trust, poor market access, and inconsistent policy support—that undermine cooperative effectiveness and farmer participation [67,68]. Many farmers perceive cooperatives as risky ventures with unclear benefits, further limiting their role as credible information intermediaries. To enhance the contribution of FCs to sustainable intensification and social innovation in agriculture, targeted policy support and capacity-building initiatives are needed [69].

Public agricultural technology extension service centers (ATESCs) were also underutilized, despite substantial government investment in reforming and expanding the public extension system [70]. Farmers' limited engagement with ATESCs may stem from their low visibility and the poor perception of their service quality. Extension agents in China spent an average of just 81 days per year in direct contact with farmers, with funding constraints limiting the intensity and reach of their services [71]. In contrast, studies from countries such as Tanzania show that public extension workers remain the primary information channel [72]. In China, however, farmers often view extension agents as government representatives rather than neutral advisers [73], which may undermine trust and engagement. Strengthening the accountability, accessibility, and agronomic relevance of public extension institutions is essential for restoring their credibility and effectiveness [74,75].

Mass media (MM), including internet platforms and television, was also rarely used by farmers for decision-making. This can be attributed to the demographic characteristics of apple growers, many of whom are older and have limited digital literacy [76,77]. While mass media can potentially deliver timely and scalable agricultural information, its impact is constrained by the variability in its content quality and contextual relevance, which often lack local specificity or scientific rigor. In particular, MM may raise farmers' general awareness of agricultural technologies, but it typically fails to address the highly localized and situation-specific challenges farmers face in their orchards [36]. Face-to-face communication remains an important mechanism for conveying nuanced or complex information [73], especially in settings where formal education or digital access is limited. However, overreliance on traditional peer-based sources (e.g., farmer peers (FPs)) may also reinforce conservative decision-making and inhibit the adoption of novel technologies [78].

The study also finds that approximately half of the surveyed farmers relied on fewer than two sources of information for management decisions (Figure 5). This limited diversity in information sources may reduce farmers' exposure to innovation, and it also reflects underlying issues related to both the credibility and accessibility of available sources. This could place farmers at a disadvantage in terms of technology adoption, as new innovations may not be included in the limited set of sources they rely on [79]. No single source is able to satisfy all of a farmer's information needs; instead, different sources often play complementary roles [37,80].

However, when encouraging farmers to diversify their information sources, it is essential to first improve the credibility of existing low-trust sources—for example, by introducing stricter regulatory standards to constrain the over-recommendation of agrochemicals by ACDs, or by increasing funding, staffing, and training support for ATESCs. Only on this basis can information diversity meaningfully improve farmers' decision-making quality. Improving the accessibility of trusted information sources through outreach, platform development, and training is essential to promoting the adoption of modern agricultural technologies.

5.2. Who Chose Which Information Source, and Implications for Technology Extension

This study found that variations in farmer demographics (e.g., age, gender, and education level) and orchard characteristics (e.g., planting area) made a difference to the preferred information source. Similar findings were also obtained in other studies [38,81,82]. For example, age was an important determinant. We found that older farmers were more likely to choose ACDs. The reason is that older farmers normally work full-time in their orchards [83], which may lead to closer ties with local dealers, compared with younger farmers who are often more mobile or diversified in their livelihood strategies. This association can be a disadvantage when ACD advice is biased toward the dealer's own product sales [84]. In terms of gender, female farmers tended to gather information from farmer peers (FPs). The reason could be that women are better integrated into the social fabric of their home villages and therefore the FP is an easy or proximal information source for them [85]. Regarding education, farmers who had a low education level more often chose local experts (EXPs) and personal experience (PE) to support their decision-making. An EXP is normally a trained and well-educated local farmer. Farmers can establish a trusted and meaningful dialog with EXPs regarding orchard management. Farmers require a certain level of education to turn new information into concrete actions [86]. In addition, farmers who had participated in agricultural training showed a stronger preference for EXPs and agricultural technology extension service centers (ATESCs), possibly due to the relationships and familiarity built during training sessions [86].

These descriptive patterns suggest that different demographic or experiential traits are associated with specific information source preferences, although no statistical classification (e.g., cluster analysis) was performed. Rather than treating these patterns as definitive typologies, they are intended to provide suggestive insights into the socio-cognitive context of farmers' information behavior.

From a policy perspective, recognizing such patterns may help in designing more targeted and inclusive extension strategies. For example, initiatives aiming to strengthen ATESC visibility and trust may prioritize outreach to farmers already familiar with formal training programs, while peer-led interventions may be more suitable for reaching female farmers. Tailoring information dissemination strategies to reflect the nuanced needs and preferences of different farmer profiles can enhance both the message relevance and adoption potential.

5.3. How Preference for Information Source Impacts Modern Agricultural Technology Adoption

We found that local experts (EXPs) could significantly increase the probability of dwarf rootstock adoption, whereas other information sources had negligible effects on their adoption (Figure 6). Successfully switching to the use of dwarf rootstocks requires a large monetary investment and a good knowledge base [87]. Farmers need to control the tree height, canopy volume, and canopy density according to natural, technical, and budgetary considerations [88,89]. This study shows that farmers generally have high levels of trust in EXPs and consider their suggestions to be reliable and high-quality sources of information, which is also consistent with findings from the existing literature [43]. This trust stems from the practical experience and advisory ability of EXPs in helping farmers address complex orchard management issues [88,90]. In addition, EXPs are familiar with the advantages of dwarf rootstocks and can provide practical, field-based guidance on tree training, apple harvesting, and pest and disease control [89]. They are also more willing to share their experience and to provide assistance if their actions benefit others, especially those with fewer resources [91]. These factors together enable EXPs to play a key role in the promotion of modern agricultural technologies.

By contrast, EXPs have limited influence over the adoption of virus-free seedlings. Virus-free seedlings are usually propagated by specialized nurseries, and both their marketing and pricing are controlled by commercial firms. EXPs can only provide suggestions regarding their adoption but lack actual influence over the companies or farmers. Moreover, the effectiveness of virus-free seedlings often takes time to become visible; before results are observable, farmers find it difficult to distinguish quality from poor seedlings, making the outcome uncertain. As a result, EXPs are generally more cautious when recommending such types of input.

On the other hand, we found that agri-chemical dealers (ACDs) could, to some extent, increase the adoption rates of virus-free seedlings (Figure 7). ACD outlets usually sell high-quality seedlings, and store owners are naturally motivated to promote virus-free seedlings to increase their profits. Selling high-value seedlings helps raise their income. In contrast, cultivation modes like dwarf-intensive planting, which require long-term field management and offer lower short-term commercial returns, are less attractive to them.

By comparison, farmers relying on personal experience (PE) showed a significant negative effect on the adoption of virus-free seedlings. This may be because personal experience is usually built on visible and tangible management outcomes, and it is less effective in recognizing diseases that are asymptomatic for long periods or have low external visibility. As a result, farmers may underestimate the potential threats of such "hidden risks" [92]. For example, the apple mosaic virus is difficult to treat and significantly reduces fruit quality [93], but its symptoms often appear only after a certain period. Compared with low-probability but high-impact risks like these, farmers are generally averse to decisions involving one-time high upfront investments in the short term.

Despite the fact that farmer peers (FPs) were the second-most frequently chosen source of information regarding management decisions, they had no significant influence on adoption behavior. This result indicates that Chinese apple growers do not exhibit the same degree of social pressure or response to social norms as seen in other countries when it comes to technology adoption [80]. One possible reason is the lack of "central farmers" in peer advisory networks—those who have demonstrated clear success in adopting new technologies and thereby achieved significantly higher incomes than their peers [94]. Therefore, policymakers may consider directing farmers' attention to those around them with rich planting experience, strong management skills, and visible outcomes and organize related demonstration and exchange activities. This would help strengthen the peer-to-peer information influence and promote the wider diffusion of modern agricultural technologies [95].

These findings suggest that different information sources exert distinct mechanisms of influence depending on the type of agricultural technology involved. This highlights the need to tailor information interventions by matching appropriate communication channels with technology characteristics in order to enhance policy effectiveness and improve resource allocation efficiency.

5.4. Impacts of Adopting New Technology on Orchard Performance

Adoption of modern cultivation technologies—particularly dwarf rootstocks and virus-free seedlings—was linked to improved orchard health and, to a lesser extent, economic performance. Farmers who adopted either of these technologies reported fewer pest- and disease-related problems compared with those using traditional cultivation systems. This is consistent with existing agronomic research demonstrating that appropriate rootstock selection enhances resistance to biotic stresses, thereby reducing vulnerability to pest and disease outbreaks [96–98]. From an economic perspective, virus-free seedlings were found to significantly improve orchard gross margins. Although these seedlings carry a higher upfront cost than conventional planting material, they should be viewed as a one-time investment that offsets long-term production risks. Previous studies have shown that virus-free seedlings reduce the need for frequent pesticide applications and lower disease management costs over time [13,99]. In addition, the use of healthy planting material contributes to improved fruit quality, which may translate into higher market prices and enhanced profitability.

In contrast, adoption of dwarf rootstock cultivation did not yield a statistically significant improvement in gross margin among the sampled farmers. This outcome may reflect the higher technical requirements and investment thresholds associated with high-density orchard systems. Evidence from prior studies suggests that the economic benefits of dwarf rootstock systems are more likely to be realized under certain enabling conditions—such as when farmers receive systematic management training, have access to reliable irrigation infrastructure, and utilize appropriate support structures like trellises or stakes [89,100]. Under these conditions, the technology can support improvements in both yield stability and fruit quality, leading to enhanced profitability. However, if these prerequisites are not met, the expected returns may not materialize, and growers could even incur additional economic losses due to poor implementation or technical inefficiencies. To address these implementation challenges and to promote the economic benefits of dwarf rootstock systems, targeted demonstration projects and systematic training programs are essential. Field-based extension activities that highlight successful cases can help bridge the technical gap and reduce perceived risks [101]. When farmers observe clear returns under proper management conditions, they are more likely to adopt and maintain these technologies. Therefore, aligning knowledge dissemination with economic incentives is critical for accelerating the transition toward more productive and sustainable orchard systems.

In addition to statistical significance, we calculated Cohen's d effect sizes to assess the magnitude of differences in management outcomes between adopters and non-adopters. The results showed large effect sizes ($|d| > 0.5$) for pest and disease reduction, suggesting meaningful practical benefits of these technologies in improving orchard health. By contrast, gross margin differences—while sometimes statistically significant—exhibited small effect sizes, indicating that the economic impact may be more modest or context-dependent. This highlights the importance of considering both statistical and practical significance when evaluating the outcomes of technology adoption.

It is important to note that the gross margin figures reported in this study are based on variable costs related to orchard management, as captured through the questionnaire. These include expenditure on fungicides, fertilizers, bagging (including labor when applicable), and irrigation. However, the calculation does not include land rent and labor costs associated with fungicide spraying and fertilization. Empirical evidence suggests that hired labor in apple orchards is mainly used for flower and fruit thinning, as well as for bagging tasks [102]. The survey results indicate that most of the sampled farmers operate small-scale orchards (less than 5 mu), where routine management work is typically performed by family members without the need to hire external labor. In contrast, larger orchards often adopt mechanized spraying and fertilization practices to reduce labor costs [8]. In addition, this survey did not collect data on land rent. Since local policies usually adjust land rent uniformly by a certain proportion every 3 to 5 years, the variation in rent among farmers is limited. Therefore, the cost structure used in this study largely reflects the actual production conditions and decision-making behavior of smallholder farmers in the study region.

Future research could incorporate the opportunity costs of family labor and land to provide a more comprehensive evaluation of the economic returns from technology adoption.

In addition, this study did not collect fruit quality indicators such as sugar content or fruit diameter, which are important parameters for assessing the commercial value of apples [103,104]. The absence of such data was primarily due to the timing of the fieldwork, which did not coincide with the harvest period, which is when quality can be accurately measured. Furthermore, collecting these indicators requires more technical effort and specialized equipment [105], which posed practical challenges during the survey. Future studies could integrate both yield and quality metrics to better evaluate the combined impact of information preferences and technological adoption on overall orchard performance.

6. Conclusions

Based on survey data from nearly 400 apple growers across major production regions in China, this study examined the role of agricultural information sources in shaping technology-adoption behavior and the associated economic outcomes. The findings highlight that agri-chemical dealers (ACDs) are the most frequently consulted source for production-related advice, followed by local agricultural experts (EXPs) and peer networks.

Notably, information provided by EXPs significantly increased the likelihood of adopting dwarf rootstock cultivation, while ACDs were the primary drivers of adoption for virus-free seedlings.

Economic analysis revealed that adopters of virus-free seedlings achieved significantly higher gross margins compared with non-adopters, underscoring the economic value of this technology. However, no significant economic advantage was observed for adopters of dwarf rootstocks, suggesting that the benefits of some innovations may be more context- or time-dependent.

These results underscore the critical role of trusted and context-relevant information sources in facilitating effective technology diffusion. Modern agricultural technologies are more likely to be adopted when information is targeted, credible, and clearly communicates economic benefits. Accordingly, policymakers and extension agencies should consider the heterogeneity of farmers' information networks and leverage influential intermediaries—such as ACDs and local experts—to improve outreach efficiency. Strengthening the alignment between information delivery mechanisms and farmers' preferences offers a viable strategy for enhancing technology adoption and promoting sustainable intensification in perennial crop systems.

This study has several limitations that merit consideration. First, the data are cross-sectional and region-specific, which may limit the generalizability of the findings to other perennial crop systems or geographic contexts. Second, although our models account for various demographic and orchard-level variables, unobserved factors—such as farmers' risk preferences or policy interventions—may also influence both their information use and technology-adoption behavior. Third, the study focuses on whether a technology is adopted rather than on how that adoption evolves, including potential adjustments or refinements in usage over time.

Future research could explore the long-term effects of information exposure on sustained adoption behavior, integrate network analysis to identify key individuals or organizations that influence information diffusion, and assess how policy interventions or large language models (LLMs) mediate the effectiveness of different information channels. Such work would provide deeper insights into the mechanisms. Underlying agricultural technology diffusion in smallholder systems and offer practical guidance for evidence-based policymaking.

In addition, future studies could also examine how farmers assess the credibility of diverse information sources and navigate conflicting advice, especially in environments where information quality is uneven.

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Institutional Review Board Statement: According to the guidelines of our institution and local regulations, ethical approval was not required for this type of survey-based research. Prior to the survey, the investigators ensured that the respondents were fully aware of the research purpose and had provided informed consent.

Data Availability Statement: The survey dataset and code have been made publicly available on Zenodo by the authors to facilitate open access: https://zenodo.org/records/15576954 (accessed on 29 October 2024).

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