frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 July 2025
DOI 10.3389/fsufs.2025.1600226

OPEN ACCESS

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RECEIVED 30 March 2025
ACCEPTED 16 June 2025
PUBLISHED 09 July 2025

CITATION
Xie Y, Liu G, Fu J, Deng H, Liu X and Chen J (2025) The impact of aging agricultural labor force on farmland abandonment and the moderating effects of agricultural technology training—a study based on data from Jiangxi Province, China. *Front. Sustain. Food Syst.* 9:1600226. doi: 10.3389/fsufs.2025.1600226

The impact of aging agricultural labor force on farmland abandonment and the moderating effects of agricultural technology training—a study based on data from Jiangxi Province, China

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Introduction: Based on the research data of 1,102 farm households in five representative counties and districts of Jiangxi Province (Anyi County, Jinxian County, Nanchang County, Wanli District, and Xinjian District) in 2020. It further explores the moderating effects of agricultural technology training on the relationship between the aging agricultural labor force and land abandonment behavior and area, as well as the heterogeneous effects of farm-pluriactivity degree and land scales on such outcomes.

Methods: This study utilizes multiple econometric models to analyze the impact of the aging agricultural labor force on land abandonment occurrence and area.

Results: The study found that: firstly, the aging agricultural labor force has positive effects on both land abandonment occurrence and its area; secondly, agricultural technology training has negative moderating effects on the impact of aging agricultural labor force on the probability of land abandonment and its area; thirdly, there is heterogeneity in the effects of farm-pluriactivity degree and land scales on land abandonment occurrence and its area. Moreover, the likelihood and area of land abandonment are greater for farmers with a high farm-pluriactivity degree than for those with a low farm-pluriactivity degree, and the likelihood and area of land abandonment are greater for farmers with large-scale lands than for those with small-scale lands.

Discussion: Therefore, this paper proposes incorporating agricultural technology training into the core policy toolbox of the rural revitalization strategy, cultivating new types of agricultural entities, and establishing a long-term training mechanism featuring "government leadership, support from scientific research institutions, and participation from cooperatives" to fundamentally address the challenges of "who will farm the land" and "how to farm the land well."

KEYWORDS

agricultural labor force, agricultural technology training, aging, land abandonment, resource endowments

1 Introduction

In the context of globalization, the aging population has become a common concern worldwide. This trend affects the economic and social development of developed countries and brings profound challenges to developing countries (Chen et al., 2024; Fang et al., 2023; Li et al., 2024). China's population has been aging at an accelerating rate in recent years. This problem is visible not only in urban areas but also in rural areas. According to the official statistics of the sixth and seventh national census in 2010 and 2021, the proportion of people aged 60 and above in the total population has significantly increased from 13.26 to 18.70%, and the proportion of people aged 65 and above has also increased from 8.87 to 13.50%. By the end of 2022, China's elderly population aged 60 and above has reached 280 million (National Health Commission of the People's Republic of China, 2021). This trend indicates that the aging population is taking on unprecedented intensity and breadth, posing a significant test for socioeconomic development.

Agriculture, the foundation of the national economy, has been acting as the "ballast" for the social and economic advancement of China. However, in 2020, the number of agricultural workers in China accounted for 36.11% of the total number of people, of which the proportion of agricultural laborers over 65 years old was as high as 17.72% (National Health Commission of the People's Republic of China, 2021). It can be seen that under the macro background of aging, the problem of the rural aging population is equally severe. As the leading supplier of agricultural labor, the aging trend could inevitably lead to the corresponding reconstruction of the agricultural labor force (Ren et al., 2023). Since China's reform and opening up 40 years ago, with the gradual improvement of medical and health conditions, the rigorous implementation of family planning policy, and the rapid advancement of urbanization and industrialization, the birth rate of China's population has gradually declined, and the life expectancy of the population has been steadily extended. This change has led to the transfer of many young and high-quality laborers to non-agricultural fields, further aggravating the aging phenomenon of the agricultural labor force. The importance of land as a core element of agricultural production is self-evident (Zhang et al., 2025). President Xi reiterated this vital principle in his report to the 20th Party Congress, emphasizing the need to "firmly guard the red line of 1.8 billion mu of arable land, and ensure that the rice bowls of the Chinese people are firmly held in their own hands." However, China faces the dual dilemma of decreasing farmland and increasing aging agricultural labor force. Amid this background, what is the specific impact of the aging agricultural labor force on land use, particularly the phenomenon of farmland abandonment? In order to explore this issue in depth, this study conducts a systematic analysis.

Scholars at home and abroad have conducted extensive research on the inducements of farmers' land abandonment behavior and the influencing factors of abandonment area, mainly focusing on three dimensions: economic interest motivation, social structure changes, and natural environment constraints. However, systematic research on the impact of aging agricultural labor on land abandonment remains insufficient.

From the perspective of economic interest motivation, one of the main causes of land abandonment is the low income from agricultural production. While the costs of agricultural production materials like seeds, fertilizer, and pesticides keep rising, the prices of agricultural goods fluctuate considerably and stay low for a long period, which leads to poor agricultural production profitability (Lanfranchi et al., 2019). For example, farmers' input–output ratios are significantly out of balance under the traditional agricultural planting model, and their earnings from farming are substantially lower than those from migrant labor (Smith, 2019). Furthermore, both market and natural risks put pressure on agricultural productivity (Khatri et al., 2024). Crop reduction probably results from natural disasters (Shi et al., 2021; Trinh et al., 2021), and farmers may find it challenging to generate steady income due to market price volatility (Lin et al., 2024). When farming is difficult to meet the family's economic needs, farmers often choose to abandon cultivation, leading to an expansion in land abandonment area (Li et al., 2021).

From the perspective of social structure changes, the acceleration of urbanization and industrialization has spurred the migration of rural labor to cities (Gu, 2019). As large numbers of young and middle-aged rural workers flock to urban areas in pursuit of higher-income employment opportunities (Clendenning, 2023), elderly individuals, women, and children are disproportionately left behind in rural regions. These groups often face challenges in engaging in high-intensity agricultural production labor (Ye et al., 2017), ultimately leading to land abandonment in certain farmland areas (Wang Y. et al., 2020). Beyond demographic shifts, structural flaws in the rural land market further exacerbate the issue, with challenges such as asymmetric information in land transfer, high transaction costs, and inadequate guarantee mechanisms (Li et al., 2020). For farmers unable to transfer their land smoothly or cultivate it themselves, abandonment becomes the only option (Li, 2022).

From the perspective of natural environment constraints, harsh natural conditions have a significant impact on farmland abandonment. In complex terrains such as mountainous and hilly areas, severe land fragmentation is not conducive to large-scale mechanized operations, resulting in high agricultural production costs and low efficiency (Yu et al., 2022; Wang J. et al., 2020; Wang X. et al., 2020; Wang Y. et al., 2020). For example, in the mountainous areas of Southwest China, due to topographical constraints, cultivated land is small and scattered, making it difficult for farmers to achieve economic benefits through large-scale cultivation, and the phenomenon of land abandonment is more prevalent (Zhang, 2023). In addition, environmental problems such as frequent natural disasters, declining soil fertility, and water shortages also reduce land productivity, forcing farmers to abandon cultivating part of their land (Brown, 2024).

In recent years, the impact of aging agricultural labor force on China's agricultural production has attracted widespread attention from all sectors of society. Although existing literature has comprehensively explored land abandonment from multiple perspectives, research directly focusing on the impact of aging agricultural labor force on the occurrence and area of land abandonment remains relatively insufficient. Most existing studies treat aging as a derivative phenomenon of rural labor outflow, failing to deeply analyze the specific mechanisms and quantitative correlations between aging and land abandonment. For example, it has not been comprehensively explained how characteristics such as physical decline and limited ability to adopt new agricultural technologies among elderly laborers influence abandonment decisions and changes in abandoned area. Therefore, subsequent research urgently needs to strengthen systematic studies on the relationship

between aging agricultural labor force and land abandonment, so as to provide more targeted theoretical foundations and policy recommendations for solving the problem of land abandonment.

2 Theoretical analysis and research hypotheses

From the perspective of labor supply, with the aging of agricultural labor force, the physical strength and energy of elderly laborers have significantly declined, making it difficult for them to undertake high-intensity and long-duration farm work (Liu et al., 2023), which directly leads to a shortage of effective labor in agricultural production. For example, in some mountainous areas with complex terrains, the degree of agricultural mechanization is limited, and a large amount of farm work needs to be completed manually. When the main labor force in a family enters old age, they often feel unable to cope with heavy tasks such as plowing, sowing, and harvesting, and have to choose to abandon cultivating part of their land (Li et al., 2023), thereby increasing the likelihood of farmland abandonment. Studies have shown that the problem of farmland abandonment is more prominent in areas with severe aging (Lee et al., 2021).

In terms of production capacity and technology adoption, elderly laborers generally have lower education levels and weaker ability to accept and learn new technologies and equipment (Charness and Boot, 2009). In today's agricultural modernization process, efficient agricultural technologies and advanced agricultural machinery are crucial for improving agricultural production efficiency and reducing labor intensity (Huang et al., 2024). However, due to their outdated knowledge structures, elderly laborers find it difficult to master new agricultural technologies such as precision irrigation and drone plant protection, and are unable to operate complex agricultural machinery proficiently, leaving agricultural production stuck in traditional and inefficient modes (Tong et al., 2024). In this case, the output benefit of land decreases, and when the income from cultivation cannot cover the costs, farmers are more inclined to abandon farming (Guo et al., 2015; Yiyuan and Changquan, 2024). Relevant research shows that households with a high proportion of elderly labor have low adoption rates of new agricultural technologies and correspondingly larger areas of farmland abandonment (Rigg et al., 2020).

In summary, the aging of rural labor has a profound impact on farmers' land use decisions by reducing the quality of labor. After weighing costs and benefits, farmers tend to abandon part of their land, especially when cultivated land conditions are poor, this phenomenon may be particularly prominent. Based on this, this paper proposes the following hypotheses:

> *H1*: The aging agricultural labor force has positive effects on both land abandonment occurrence and its area.

In the economic dimension, farmers, as rational participants in economic activities, face the dilemma of high labor intensity, limited returns in non-agricultural industries, and high living cost of migrating to work, agricultural technology training has emerged as a meaningful solution to the problem (Sui et al., 2021). By teaching new technologies and methods, agricultural technology training reduces the over-dependence of agricultural production on labor (Chang, 2016) and improves the efficiency of agricultural production of farm households (Liu et al., 2022), which in turn enhances the yield and quality of agricultural products, thereby raising farm incomes (Mgendi et al., 2021). This change not only encourages young and middle-aged laborers who were previously employed in non-agricultural industries to return to farming, but it also effectively enhances the quantity and quality of effective workers in farm households, mitigating the adverse impact of aging rural workers on farmland abandonment (Xiong et al., 2006). In the natural dimension, agriculture is an industry that is more subject to natural constraints, especially in remote mountainous areas where agricultural production is fraught with obstacles. Agricultural technology training becomes the most direct path for farmers to update their techniques and solve their technology claims (Jaiswal et al., 2019). By improving agricultural technology training, the quality of human capital can be enhanced and the positive role of human capital in agricultural production can be realized (Hoang-Khac et al., 2022). This can not only help farmers cope with the constraints of natural conditions but also mitigate the aggravation of farmland abandonment by improving agricultural productivity.

Agricultural technology training can also reduce the demand for rural labor and promote the optimal allocation of farmland resources. In the face of the aging agricultural labor force, farmers can reduce the demand for labor through agricultural machinery technology or agricultural machinery combined with modern biotechnology and choose to transfer abandoned land to farmers capable of farming. This approach alleviates the labor supply shortage in rural areas, effectively utilizes arable land resources, and reduces land abandonment. In conclusion, agricultural technology training mitigates the aggravating effect of the aging agricultural labor force on the farmland abandonment area by improving the quality of human capital, reducing the demand for rural labor, and promoting the optimal allocation of farmland resources. Based on this, this study proposes the following research hypotheses:

> *H2*: Agricultural technology training has negative moderating effects on the impact of aging agricultural labor force on the land abandonment occurrence and its area.

The aging agricultural labor force affects the area of farmland abandonment primarily through two dimensions. From the dimension of farm-pluriactivity differentiation, there is a significant trend of "sideline production" in Chinese agriculture, with the share of agricultural income in farmers' income gradually decreasing, and farmers no longer depend solely on agriculture to support their life (Wu, 2017). This "sideline production" phenomenon has reduced the time investment of elderly farmers in agricultural production (Jiang et al., 2022). When the income from non-agricultural employment exceeds farm operations, farm-pluriactivity households are less motivated to engage in farm production (Neglo et al., 2021). They may cultivate less land or even stop engaging in agricultural production completely, thus leading to farmland abandonment (Liu and Zhou, 2014). From the dimension of land scale differentiation, the area of farmland and land quality are essential constraints on effective land use. The larger the area of farmland, the higher the cost of labor and financial and material resources required, which to some extent, constrains the effective use of arable land (Wang J. et al., 2020; Wang X. et al., 2020; Wang Y. et al., 2020). With the aging agricultural labor force and the lack of sufficient labor to operate large areas of land, farmers may leave part of the land directly abandoned to reduce production costs and the labor burden (Huang and Li, 2009).

To summarize, farmers' decisions about how to utilize farmland are influenced by the aging agricultural labor force in two ways: farm-pluriactivity and land size differentiation, which leads to an increase in the farmland abandoned. Therefore, this study proposes the following research hypothesis (see Figure 1):

> *H3*: There is heterogeneity in the effects of farm-pluriactivity degree and land scales on land abandonment occurrence and its area.

3 Research design

3.1 Data sources

Jiangxi Province, located between latitudes 24°29′14″ and 30°04′43″ north and longitudes 113°34′18″ to 118°28′56″ east, is renowned as a traditional agricultural region and a significant grain-producing area in China. Moreover, it plays a crucial role in the nationwide poverty alleviation efforts. As of June 2020, Jiangxi comprised 61 counties, 12 county-level cities, 27 municipal districts, 61 municipalities, and a total of 100 county-level divisions. Among them, 58 counties (including cities and districts) were identified as former Central Soviet Union regions and areas facing special hardships, highlighting their significance as key regions in the battle against poverty.

To deeply explore the progress of traditional agriculture and the effectiveness of poverty alleviation in Jiangxi Province, the data used in this paper comes from the data of 1,102 farm household surveys conducted by the group in July–August 2020 in Jiangxi Province, and field research and interviews were conducted on the situation of rural land abandonment. According to the level of regional socio-economic development in Jiangxi Province, stratified random sampling was used to select the sample counties, respectively, 10 traditional agricultural districts in the northern part of Jiangxi Province, and 2 sample villages in each sample county (city), adopting the principle of combining typical and random sampling, and conducting the research in the form of face-to-face interviews. The sample selection method is as follows: firstly, a set of indicator system including economic development level, rural development level, land status, resource and environmental conditions, etc. is constructed by county and district; considering the representativeness and typicality of the districts and counties, a total of 5 sample counties and districts (Anyi County, Jinxian County, Nanchang County, Wanli District, Xinjian District) are selected. Secondly, in the samples, according to the land abandonment situation of each village and the distance from the township government, and from the local government to obtain a list of local land abandonment for random selection, a total of 1,164 samples were investigated. After the completion of the research according to the principle of consistency and the emergence of large gaps in the information questionnaire after the deletion, this paper finally selected 1,102 samples of rural land abandonment data for empirical analysis, the sample validity rate of 94.67 percent.

3.2 Variable selection

3.2.1 Explained variables

Based on the concept of land abandonment and drawing on existing research practices (Zheng, 2022; Zheng and Luo, 2019), two proxy variables—land abandonment occurrence and land abandonment area—are selected to measure land abandonment as the explained variables in this study. Whether land abandonment occurs is a binary variable (0 = no abandonment, 1 = abandonment), while the land abandonment area is a continuous variable.

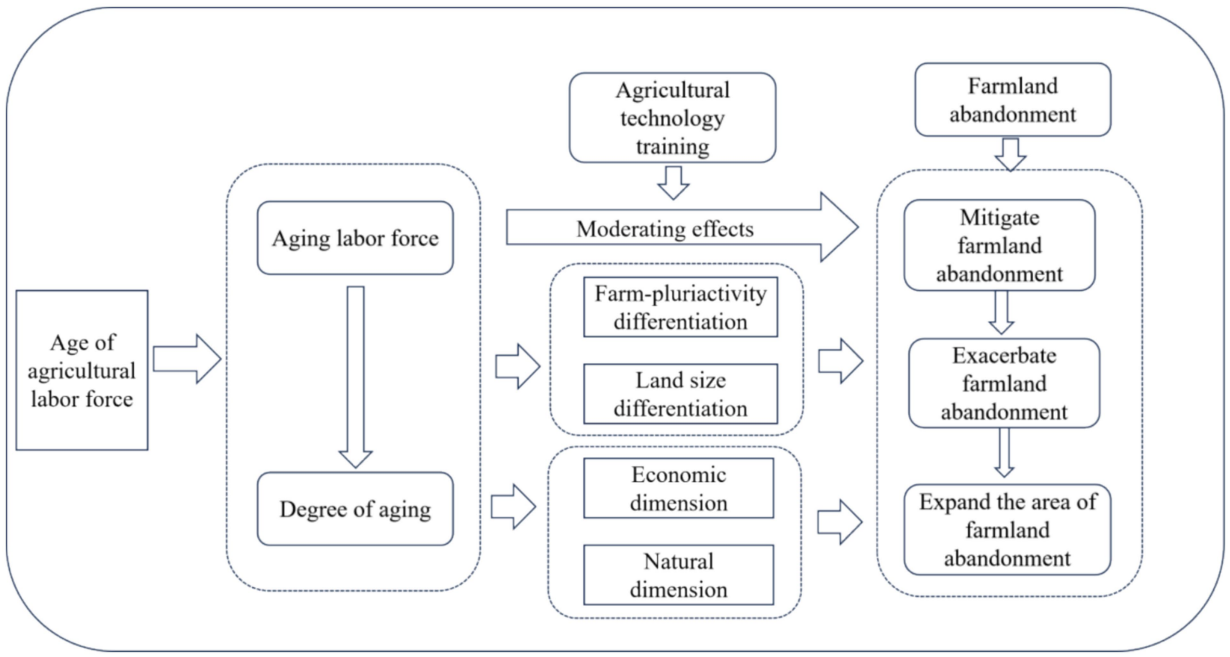

FIGURE 1
Theoretical framework.

3.2.2 Explanatory variable

Compared with indicators reflecting individual age such as the head of household's age and the age of agricultural management decision-makers, whether the average age of all agricultural laborers in the household exceeds 60 years old can better reflect the aging agricultural labor at the household level (Mestres Domènech et al., 2020; Zhu, 2023). Therefore, drawing on the approach of Wang and Tian (2018), this paper introduces a dummy variable for elderly farmer household, with the criterion for judgment being whether the average age of all agricultural laborers in the household exceeds 60 years old. This variable is used as the core explanatory variable. If the average age of the household's entire labor force exceeds 60 years old, the value is set to 1; otherwise, it is set to 0.

3.2.3 Moderating variable

Referring to the existing research (Yuan et al., 2023), this study uses whether the farmers have participated in agricultural technology training as the moderating variable, which takes the value of 1 if the farmers have participated in agricultural technology training and 0 otherwise.

3.2.4 Control variables

To ensure the reliability and rationality of the regression analysis results, drawing on existing research (Zheng, 2022; Zheng and Luo, 2019), this study incorporates common variables of farmer behavior, including individual characteristics (health), family characteristics (number of laborers, proportion of family care responsibilities, logarithm of annual total income, and whether the household has joined a farmers' cooperative), and agricultural production characteristics (fertility of arable land, irrigation conditions of arable land, and exposure to meteorological disasters). Meanwhile, to avoid omitting control variables and improve the stability of empirical results, this paper adds village-level characteristic variables to account for omitted variables, including the distance from the village committee to the township government, the village's relative economic strength within the county, whether the village is located in or near a nature reserve, and the hardening rate of the village's main roads.

3.3 Descriptive analysis

Based on the research data, this study found that of the 1,102 rural households that participated in the research, a total of 277 households, or 20.6% of the total sample, had land abandonment. Meanwhile, the average total area of abandoned land was 1.863 mu, with a maximum of 85 mu, showing a relatively serious land abandonment situation. In terms of the aging of agricultural labor, the mean value of whether the average age of the entire family's labor force exceeds 60 years old is 0.184, indicating that 18.4% of the sample farmers are elderly households. The aging problem of agricultural labor is relatively prominent, providing effective support for follow-up research. Regarding agricultural technology training, 59.8% of the sample farmers had participated in agricultural technology training, showing a high popularization rate of agricultural technology training. From the perspective of individual characteristics of farmers, their physical conditions are generally good. In terms of family characteristics, the sample farmers had more than 2 family laborers and more than 4 total family members, with only 29.9% participation rate in farmer cooperatives. Regarding agricultural production characteristics, the fertility level of cultivated land and irrigation conditions for the sample farmers were at a general level, with an average of one meteorological disaster per year. From the perspective of village characteristics, the economic strength of the villages where the sample farmers lived was relatively balanced within their respective counties, and most were not located in or around nature reserves. The main roads in the villages had a high degree of hardening, indicating better transportation conditions in the villages (see Table 1).

3.4 Model construction

3.4.1 Binary logistic regression model

Given that both continuous and binary categorical variables are present among the explained variables, a linear regression model is employed for the analysis. The variables are sequentially introduced into the model one by one, with the specific settings described as follows:

$$Y_1 = \gamma_{10} + \gamma_{11}Age60 + \sum \gamma_{1i}Controls + \varepsilon \quad (1)$$

$$Y_2 = \gamma_{20} + \gamma_{21}Age60 + \sum \gamma_{2i}Controls + \varepsilon \quad (2)$$

Y_1 is one of the explained variables of the model, which represents the land abandonment occurrence, and Y_2 is another explained variable of the model, which represents the land abandonment area. $Age60$ is the core explanatory variable of Equations 1, 2, that is, whether the average age of labor force of the whole family is more than 60 years old. γ_0 is the intercept term, $\gamma_{10}, \gamma_{11}, \gamma_{1i}, \gamma_{20}, \gamma_{21}, \gamma_{2i}$ is the impact coefficient, if the coefficient is positive it indicates a positive facilitating effect on farmers' land abandonment, and vice versa, it is a negative inhibiting effect. Controls represent a series of control variables containing: health, number of people in the labor force, percentage of home care, logarithm of total annual income, whether or not they are members of farmers' cooperatives, degree of fertility of arable land, irrigation conditions of arable land, meteorological hazards, relative economic strength of the village in the county, whether the village is located around a nature reserve, and the hardening rate of the main road of the village. ε is the random error term.

3.4.2 Moderating effects model

Based on the linear regression model, this paper introduces the interaction term between whether the average age of the whole family's labor force exceeds 60 years old and agricultural technology training to identify the moderating effects of agricultural technology training on land abandonment under the background of farmer aging. The moderating effects model is specified as follows.

$$Y = \beta_0 + \beta_1 Age60 + \beta_2 Tec + \beta_3 \left(Age60 \times Tec\right) + \sum_{i=4}^{14} \beta_4 Control_i + \varepsilon \quad (3)$$

In Equation 3, agricultural technology training Tec is the moderating variable, $\beta_0, \beta_1, \beta_2, \beta_3, \beta_i$ is the regression coefficient, ε is the random error term, and the other variables are defined as in Equation 1, if the interaction term $Age60 \times Tec$ is significant, then agricultural technology training has moderating effects.

TABLE 1 Variable definitions.

Variable symbol	Variable name	Assignment method	Sample size	Mean	Standard deviation	Minimum	Maximum
Aba	Farmland abandonment	Whether or not there is farmland abandonment: Yes = 1, No = 0	1,102	0.251	0.434	0	1
Ara	Total area of abandoned farmland	Total area of farmland abandonment (acres)	1,102	1.863	6.703	0	85
Age60	Average age of family labor force ≥60	Whether the average age of the family's labor force is ≥60: Yes = 1, No = 0	1,102	0.184	0.388	0	1
Tec	Agricultural technology training	Participation in agricultural technology training: Yes = 1, No = 0	1,102	0.598	0.491	0	1
Noa	Non-agricultural income	Non-agricultural income (yuan)	1,102	30,945	47,774	0	524,000
IYL	Logarithm of total annual income	Natural logarithm of annual gross income	1,102	11.07	1.207	0	13.65
LanA	Total land area	Total land area (acres)	1,102	48.25	41.60	0	362
Heal	Health status	Severe illness = 1; Minor illness = 2; Fair = 3; Healthy = 4; Very healthy = 5	1,102	4.029	1.065	1	5
Lab	Number of laborers	Number of persons (persons)	1,102	2.755	1.188	0	7
Fac	Percentage of family care	Percentage of family care	1,102	0.364	0.264	0	1.250
IYL	Logarithm of total annual income	Natural logarithm of annual gross income	1,102	11.07	1.207	0	13.65
Co	Farmers' cooperative	Whether or not in farmers' cooperatives: Yes = 1, No = 0	1,102	0.299	0.458	0	1
Fer	Fertility of arable land	Degree of fertility of arable land: Very poor = 1; Poor = 2; Fair = 3; Good = 4; Very good = 5	1,102	3.378	1.086	1	5
Irr	Irrigation conditions of arable land	Cropland irrigation conditions: Very poor = 1; Poor = 2; Fair = 3; Good = 4; Very good = 5	1,102	3.250	1.164	1	5
Cli	Meteorological disaster	Meteorological disasters (times)	1,102	1.097	1.913	0	14
Dis	Distance of the village committee from the township government	Distance of the village committee from the township government (km)	1,102	21.02	19.83	0.500	180
Eco	Relative economic strength of the village	Relative economic strength of the village: Very poor = 1; Poor = 2; fair = 3; Good = 4; Very good = 5	1,102	3.060	0.806	1	5
Nat	Whether or not the village located in and around a conservation area	(No = 0; within 3 km of zone = 1; pilot zone = 2; buffer zone = 3; core zone = 4)	1,102	0.652	1.007	0	4
Roa	Hardening rate of main roads in the village	Hardening rate of main roads (%)	1,102	0.962	0.0745	0.700	1

4 Results and analysis

4.1 Analysis of the aging agricultural labor force and the farmland abandonment

This study employs Stata 17 econometric software for analysis, with the core explanatory variable in the model being whether the average age of the household labor force exceeds 60 years. The regression results are presented in Table 2. In Column (1), a Logistic model is used to investigate the effect of the core explanatory variable on the land abandonment occurrence, while Column (2) adopts a linear regression model to examine its impact on the land abandoned area. Additionally, the R^2 values for Columns (1) and (2) are 0.6127 and 0.3034, respectively, exhibiting a good overall fit of the models. In Column (1), the coefficient of Age60 is 4.2203 and is significant at the 1% level. A possible explanation is that as agricultural labor aging intensifies, the shortage of sufficient

TABLE 2 Benchmark regression.

Variable symbol	(1)	(2)
	Whether or not there is a land abandonment	Land abandonment area
Age60	4.2203*** (11.82)	7.3756*** (14.84)
Heal	−0.4939*** (−4.49)	−0.1193 (−0.69)
Lab	−0.7841*** (−6.54)	−0.1461 (−0.96)
Fac	0.3205 (0.65)	0.3841 (0.57)
IYL	0.8498*** (5.22)	0.2107 (1.47)
Co	−1.5312*** (−4.55)	−0.4529 (−1.19)
Fer	−1.0419*** (−7.09)	−0.2854 (−1.42)
Irr	0.0419 (0.34)	−0.3096* (−1.70)
Cli	0.1163** (2.08)	0.4036*** (4.04)
Dis	−0.0110 (−1.55)	−0.0076 (−0.87)
Eco	0.3229** (2.21)	0.0788 (0.36)
Nat	−0.0154 (−0.12)	−0.2964* (−1.69)
Roa	−1.4959 (−0.92)	−1.8911 (−0.80)
_cons	−3.9161 (−1.64)	2.5080 (0.84)
N	1,102	1,102
Pseudo R^2/R^2	0.6127	0.3034
LR chi^2 (13)/F	761.43	36.4589

t statistics in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

labor to manage large areas of land may lead farmers to abandon part of their land directly, thereby reducing production costs and labor burdens—this finding supports Hypothesis 1. From the perspective of control variables, the coefficients of health status (Heal) and labor quantity (Lab) are both statistically significantly negative, indicating that higher family members' health levels and more abundant labor resources reduce the probability of land abandonment, which highlights the role of family labor quality in agricultural land use. The coefficient of the logarithm of annual income (IYL) is significantly positive, suggesting that families with better economic conditions are more likely to abandon land. The coefficients on whether or not to join a farmers' cooperative (Co) and the fertility of arable land (Fer) are −1.5312 and −1.0419, respectively, which suggests that the better the land resource endowment, the less inclined farmers are to abandon their land. The Logistic model's results are in line with Column (2)'s Age60 coefficient of 7.3756, which is significant at the 1% level and supports Hypothesis 1. The coefficients of the Village Characteristics Variables, Eco, Nat, and Roa are negative, and the coefficient of Irrigation Condition (Irr) is −0.3096, indicating that the land abandonment area is smaller in rural areas with well-equipped irrigation facilities and environmental protection policies. Moreover, the coefficients of meteorological hazards (Cli) are significantly positive, indicating that the more frequent the meteorological hazards are, the larger the area of abandoned land is likely to be.

4.2 Robustness tests

To reduce the bias in results caused by data anomalies and variable omissions, and to ensure the robustness of the results, this paper conducts robustness tests on the estimation results of the benchmark regression from two aspects: replacing the regression model and changing the explained variable (see Table 3).

On the one hand, in order to verify whether the effect of aging on the land abandonment occurrence is robust, the regression is re-conducted by replacing the Logistic model with a Probit model, and whether or not abandonment is used as an explained variable. The results are shown in Column (1) of Table 4. From the regression results, the regression coefficient of Age60 is 2.3335, which is significantly positive at the 1% level, indicating that the more severe the aging agricultural labor, the more prone to land abandonment.

On the other hand, this paper replaces the explained variable from the land abandonment area with the logarithm of the land abandonment area, and uses a linear regression model to conduct a robustness test. The results are shown in Column (2) of Table 4. Among them, the coefficient of Age60 is 1.3359, which passes the 1% significance test. It is consistent with the coefficient direction of the land abandonment area in the benchmark regression, both being positive and the significance level not decreasing. Column (2) shows that the more severe the aging of agricultural labor, the larger the area of farmland abandonment. In summary, the results of Columns (1) and (2) are similar, further verifying the robustness of Hypothesis 1 (see Table 5).

4.3 Endogeneity analysis

In the study exploring the impact of aging agricultural labor on land abandonment, issues such as omitted variable bias and measurement error interference may exist. To ensure the reliability of research conclusions, this paper uses the Propensity Score Matching (PSM) method to re-test the model. First, the endogeneity faced by the model may originate from omitted variable bias. Although the model includes 12 control variables such as health status and the number of labor forces, unobserved individual characteristics or environmental factors may still exist, such as farmers' agricultural management preferences and the perfection of the land transfer market, which may simultaneously affect the grouping of households with an average family labor age exceeding 60 and land abandonment, leading to biased estimation results. Moreover, the endogeneity may stem from measurement error interference as some control variables, such as land fertility and the number of meteorological disasters, may have subjective evaluation errors or incomplete data records, causing deviations between measured values and true values of variables and thereby triggering endogeneity. To address these issues, this paper estimates the association between the aging agricultural labor force and all control variables through Logistic regression to generate a propensity score, which comprehensively reflects the impact of household characteristics on aging grouping. Before matching, the average Aba value was 0.892 for households with higher aging in the experimental group, which was significantly higher than 0.107 in the control group, and the ATT value was 0.785 and significant at the 1% level, indicating a significant endogeneity difference. Subsequently, matching based on propensity scores ensured that the experimental and control groups had consistent distributions in observable variables (e.g., health status, family care burden, and cultivated land conditions), thereby reducing interference from observable omitted variables. Additionally, by using multiple matching methods such as k-nearest

neighbor matching, caliper matching, caliper K-nearest neighbor matching, kernel matching to estimate, the difference in land abandonment proportions between the control groups under different matching methods after matching was small, and the results demonstrated that all ATT values were significantly positive, indicating core conclusions were not affected by the choice of matching methods, further reducing endogeneity bias caused by measurement errors or accidental factors. In conclusion, after excluding potential endogeneity issues, the promoting effect of the aging of agricultural labor force on land abandonment still exists.

4.4 Analysis of the moderating effects of agricultural technology training

According to the previous theoretical analysis, agricultural technology training may have moderating effects on the impact of the aging agricultural labor force on farmland abandonment. To verify the moderating effects of agricultural technology training on the impact relationship between the two, this study introduces the interaction term between agricultural technology training and the aging agricultural labor force for regression test.

Table 6 shows the results of moderating effects of agricultural technology training on whether land abandonment occurs after incorporating other control variables. The results of Column (1) exhibit that when the moderating variable is not considered, the aging of agricultural labor has a positive impact on land abandonment occurrence at the 1% significance level, indicating that the aging of agricultural labor can increase the possibility of land abandonment. In Column (2), after introducing the variable of whether farmers participate in agricultural technology training, the regression analysis results show that participating in agricultural technology training has negative impacts on land abandonment occurrence at the 1% significance level, indicating that technology training itself can significantly reduce the incidence of land abandonment by farm households, possibly by improving production efficiency and reducing labor intensity. In Column (3) with the interaction term added, the interaction term coefficient is −16.660, the standard error is as high as 1326.679, and it does not pass the significance test. Although the coefficient sign is negative, due to the extremely large standard error, the stability of the estimation result is insufficient, which may be affected by the small variation of technology training or measurement errors in the sample. In conclusion, agricultural technology training itself can significantly reduce the land abandonment occurrence, but its effect on aging agricultural labor needs further study.

Table 7 shows the analysis results of the moderating effects of agricultural technology training on the land abandonment area after incorporating other control variables. Among them, Column (3) adds the interaction term Age*60Tec, and its interaction term coefficient is −1.790, which passes the 10% significance test, indicating that every 1 unit increase in the level of agricultural technology training weakens the positive effect of aging on the area of land abandonment by 1.790 units. This result is significant, confirming the moderating role of agricultural technology training, thus verifying Hypothesis 2.

TABLE 3 Robustness test.

Variable symbol	(1) Replace the regression model	(2) Change the explained variable
	Whether or not there is land abandonment	Logarithm of the land abandonment area
Age60	2.3335*** (12.88)	1.3359*** (30.66)
Heal	−0.2659*** (−4.50)	−0.0289* (−1.91)
Lab	−0.4180*** (−6.55)	−0.0617*** (−4.61)
Fac	0.2338 (0.89)	−0.0179 (−0.30)
IYL	0.4432*** (5.10)	0.0442*** (3.52)
Co	−0.8339*** (−4.79)	−0.1036*** (−3.10)
Fer	−0.5457*** (−7.25)	−0.0646*** (−3.66)
Irr	0.0006 (0.01)	−0.0575*** (−3.60)
Cli	0.0705** (2.28)	0.0670*** (7.64)
Dis	−0.0064*	−0.0011 (−1.51)
	(−1.66)	
Eco	0.1801** (2.27)	0.0500*** (2.63)
Nat	−0.0086 (−0.13)	−0.0108 (−0.70)
Roa	−0.7175 (−0.82)	−0.1820 (−0.88)
_cons	−2.0963 (−1.64)	0.3756 (1.44)
N	1,102	1,102
Pseudo R^2/R^2	0.6137	0.6583
LR chi^2 (13)/F	762.58	161.2650

t statistics in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

4.5 Heterogeneity analysis

Considering that there is heterogeneity in the effect of aging agricultural labor force on land abandonment, this paper conducts heterogeneity analysis according to the degree of farm-pluriactivity and land size. The findings are displayed in Tables 7, 8.

4.5.1 Heterogeneity analysis of farm-pluriactivity degree

Columns (1) and (3) and Columns (2) and (4) in Table 7 represent the regression results for high and low degrees of farm-pluriactivity, respectively. In Columns (1) and (2), Whether there is land abandonment is used as the explained variable, and whether the average age of the whole family's labor force is more than 60 years old is set as a measure of aging in agriculture, and the other relevant variables are the control variables. The regression results illustrate that the regression coefficients of the agricultural aging variable are 4.7055 and 4.1311 in the two groups of high degree of farm-pluriactivity and low degree of farm-pluriactivity, respectively, and both of them are positively significant at the 1% level. It suggests that among agricultural laborers over 60 years of age, farm households with a high degree of pluriactivity are more likely to engage in land abandonment compared to those with a low degree of pluriactivity. There is a significant difference between the two, within the same group, farm households above 60 also show a higher degree of land abandonment than those below 60. The regression results in Column (3) and Column (4) further validate the finding in Column (1) and Column (2) that a high degree of farm-pluriactivity implies that more of the agricultural population is engaged in non-agricultural work. With the

TABLE 4 PSM estimation results.

Variable symbol	Matching method	Experimental group	Control group	ATT	SD	T-value
Age60	Pre-matching	0.892	0.107	0.785***	0.024	32.63
	k-nearest neighbor matching	0.892	0.366	0.525***	0.041	12.72
	Caliper matching	0.892	0.379	0.512***	0.043	11.79
	Caliper k-nearest neighbor matching	0.892	0.354	0.538***	0.031	17.42
	Kernel matching	0.892	0.525	0.366***	0.041	12.72

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

TABLE 5 Moderating effects of agricultural technology training on the land abandonment occurrence.

Variable symbol	(1)	(2)	(3)
Age60	4.234*** (0.358)	4.182*** (0.418)	19.817 (1326.679)
Tec		−2.452*** (0.289)	−2.111*** (0.299)
Age60*Tec			−16.660 (1326.679)
_cons	−5.685** (2.717)	−4.064 (3.084)	−3.568 (3.082)
N	1,102	1,102	1,102
R^2	0.616	0.687	0.697
Adjusted R^2	0.614	0.685	0.695

t-values in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

TABLE 6 Moderating effects of agricultural technology training on land abandonment area.

Variable symbol	(1)	(2)	(3)
Age60	7.363*** (0.490)	7.219*** (0.511)	7.755*** (0.601)
Tec		−0.369 (0.374)	−0.117 (0.403)
Age60*Tec			−1.790* (1.059)
_cons	7.310** (3.062)	7.443** (3.065)	7.246** (3.065)
N	1,102	1,102	1,102
R^2	0.325	0.326	0.327
Adjusted R^2	0.316	0.316	0.317

t-values in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

increase of age, the physical fitness of farm households gradually declines, making it difficult for arduous agricultural labor to provide sufficient economic support, which leads to an increase in the land abandonment areaand a greater tendency for farm households to earn necessary income through work other than agriculture. Consequently, the problem of land abandonment is likely to worsen with the aging agricultural population.

4.5.2 Heterogeneity analysis of land size

Based on all survey data, this paper divides the samples into two groups: large-scale land and small-scale land, using the median of the total land area. Land area above the median are classified as large-scale, while those below are classified as small-scale, and this classification aims to further explore how agricultural labor aging affects land abandonment.

In Table 8, Columns (1) and (3) show the regression results for large land-scale farmers, while Columns (2) and (4) correspond to the regression results for small land-scale farmers. The regression results in Column (1) and (2) demonstrate that the average age of the whole family labor force over 60 years old has a significant positive effect on land abandonment at the 1% significance level, which is significant in both sample groups. The effect of the aging agricultural labor force on land abandonment is more significant in large land-scale farmers compared to small land-scale farmers. The regression results in Column (3) and (4) further verify the above findings. This outcome can be attributed to the fact that land transfers, which are typically high-quality transfers, are the main cause of the creation of large-scale land. Such prime agricultural land is often dedicated to high-value-added crops that demand frequent delicacy management and the adoption of modern agricultural technologies. Consequently, the disparity in land quality is exacerbated, leading to a higher likelihood of abandoning low-quality privately contracted land. This suggests that the expansion and centralized management of land can coexist with the strategic abandonment of substandard plots.

5 Conclusions and policy implications

5.1 Conclusion and discussion

Based on data from 1,102 farm household surveys in Jiangxi Province in 2020, this study investigated the impact of the aging agricultural labor force on the land abandonment behavior and area of farm households at the micro level. Analyzing the differences in land abandonment behavior among different groups reveals the profound impacts of rural land use in the context of aging from the dimensions of occurrence and area expansion. The study results show that the aging agricultural labor force has positive effects on both land abandonment occurrence and its area (H1). This finding indicates that aging is one of the important factors leading to land abandonment. In addition, the study finds that agricultural technology training has moderating effects on the impact of aging agricultural labor force on the land abandonment occurrence and its area (H2). This suggests that by improving the quality and skill of agricultural labor, technology training can indirectly reduce the land abandonment rate, providing theoretical support for agricultural production in the context of aging. At the same time, farm-pluriactivity degree and land scale have heterogeneous impacts on the land abandonment occurrence and the area (H3), especially among farmers with a high farm-pluriactivity degree and large-scale land.

TABLE 7 Heterogeneity test I.

Variable symbol	(1) High degree of farm-pluriactivity	(2) Low degree of farm-pluriactivity	(3) High degree of farm-pluriactivity	(4) Low degree of farm-pluriactivity
	Whether or not there is a land abandonment	Whether or not there is a land abandonment	Area of land abandonment	Area of land abandonment
Age60	4.7055*** (7.35)	4.1311*** (8.32)	8.3199*** (10.51)	6.3802*** (10.12)
Heal	−0.4089*** (−2.59)	−0.5938*** (−3.49)	−0.2877 (−1.08)	−0.0299 (−0.13)
Lab	−1.0117*** (−5.59)	−0.5495*** (−3.14)	−0.2550 (−1.02)	−0.0217 (−0.12)
Fac	−0.1365 (−0.19)	1.0101 (1.32)	0.5901 (0.53)	0.4118 (0.49)
IYL	0.3002 (1.14)	1.1778*** (4.34)	0.6052 (1.44)	0.0806 (0.53)
Co	−1.5587*** (−3.35)	−1.7226*** (−3.05)	−0.2957 (−0.49)	−0.5566 (−1.16)
Fer	−1.2520*** (−5.74)	−0.8686*** (−4.07)	−0.0663 (−0.20)	−0.4659* (−1.89)
Irr	0.2382 (1.39)	−0.2250 (−1.16)	−0.3640 (−1.30)	−0.2962 (−1.27)
Cli	0.1865** (2.35)	0.0664 (0.80)	0.4805*** (3.14)	0.2745** (2.13)
Dis	−0.0045 (−0.46)	−0.0147 (−1.45)	−0.0094 (−0.69)	0.0011 (0.10)
Eco	0.0728 (0.35)	0.5322** (2.47)	0.1725 (0.48)	−0.0309 (−0.12)
Nat	0.1189 (0.68)	−0.0951 (−0.45)	−0.3014 (−1.08)	−0.3415 (−1.55)
Roa	−1.8520 (−0.84)	0.0005 (0.00)	−5.9028 (−1.51)	1.6889 (0.59)
_cons	3.8524 (1.07)	−9.7145** (−2.55)	1.7595 (0.29)	0.6576 (0.19)
N	552	550	552	550
Pseudo R^2/R^2	0.6371	0.6214	0.3278	0.2806
LR chi^2 (12)/F	428.99	345.47	20.18	16.08

t statistics in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

The main contributions of this study are as follows: first, previous studies mostly explored the impact of aging agricultural labor on land abandonment, or analyzed the effects of agricultural technology training in isolation. This study groundbreakingly takes agricultural technology training as a moderating variable, places it in the relationship between aging agricultural labor and land abandonment, and splits land abandonment into two perspectives: whether abandonment occurs and abandonment area, to explore the dynamic mechanism among the three. This cross-disciplinary perspective breaks the limitations of traditional "single-factor analysis," reveals the complex correlation of "aging—technology training—land abandonment" from the perspective of systems theory, and provides a new dimension for understanding agricultural development issues; second, by introducing provincial agricultural statistical data and household survey data (Gao et al., 2023; Tong et al., 2021), and using methods such as structural equation modeling and mediating effect tests, it accurately verifies the moderating role of agricultural technology training. Compared with single data sources or simple correlation analysis, this method can better capture the complex relationships between variables, enhancing the reliability and universality of research conclusions, and providing methodological references for follow-up studies; third, when examining the impact of aging on land abandonment, it fully considers the differential behaviors of different groups, deeply reveals the mechanism of land abandonment under the background of labor aging, and provides a scientific basis for precise and customized policies in the future.

Although this study has achieved relatively adequate results, there are some limitations. First, since the data only came from Jiangxi Province, the results may have regional limitations and be challenging to generalize directly to other regions. Second, the study used cross-sectional data from a year in 2020, making it challenging to reflect the long-term dynamic changes of land abandonment. Finally, although the age and income of farm households were analyzed, other factors that may influence land abandonment behavior (such as educational level and non-agricultural employment) were not taken into account. Future research will expand the grouping criteria by adding regional and yearly data to investigate broader trends and variability in land abandonment behavior.

5.2 Policy implications

First of all, it is imperative to promote agricultural science and technology and foster new Chinese farmers. The key to improving agricultural productivity is guiding farmers to adopt science and technology and actively implement scientific farming. The government should improve agricultural production conditions, especially water conservancy and infrastructure development, to ensure effective management under drought and flood conditions. Second, the government should advocate land transfer and centralization and promote moderate scale operation of farmland. Through the transfer and concentration of land, it is feasible to effectively use abandoned land, promote appropriate large-scale operations, raise land output rates, and increase farmers' earnings. Governments at all levels need to transfer land surpluses and deficits more effectively and properly deal with the conflicts

TABLE 8 Heterogeneity test II.

Variable symbol	(1) Large-scale land	(2) Small-scale land	(3) Large-scale land	(4) Small-scale land
	Whether or not there is a land abandonment	Whether or not there is a land abandonment	Area of land abandonment	Area of land abandonment
Age60	5.6937*** (7.19)	3.7602*** (8.71)	8.9165*** (10.73)	5.4839*** (10.19)
Heal	−0.3540* (−1.92)	−0.6734*** (−4.42)	0.1118 (0.39)	−0.3663** (−1.98)
Lab	−1.1349*** (−5.51)	−0.5738*** (−3.31)	−0.4294* (−1.67)	0.0499 (0.29)
Fac	0.2348 (0.29)	0.0522 (0.08)	−0.5472 (−0.47)	1.0020 (1.39)
IYI	0.8649*** (3.39)	0.8403*** (3.54)	0.3531 (1.28)	0.0903 (0.62)
Co	−1.7956*** (−3.47)	−1.3690*** (−2.88)	−0.7917 (−1.28)	−0.2572 (−0.61)
Fer	−1.5930*** (−6.33)	−0.7101*** (−3.52)	−0.4342 (−1.37)	−0.1012 (−0.44)
Irr	0.2496 (1.33)	−0.1291 (−0.70)	−0.1814 (−0.64)	−0.4808** (−2.25)
Cli	0.0619 (0.64)	0.1723** (2.33)	0.5607*** (3.54)	0.1949* (1.70)
Dis	−0.0064 (−0.67)	−0.0183* (−1.76)	−0.0148 (−0.99)	−0.0033 (−0.36)
Eco	0.5178** (2.36)	0.1548 (0.70)	0.3421 (0.99)	−0.3910 (−1.58)
Nat	−0.2877 (−1.25)	0.1508 (0.87)	−0.5291* (−1.71)	−0.1354 (−0.74)
Roa	−0.6598 (−0.23)	−3.2060 (−1.53)	−2.0139 (−0.46)	−2.6016 (−1.09)
_cons	−3.8795 (−1.05)	−1.9859 (−0.58)	0.8679 (0.16)	6.0205* (1.90)
N	561	541	561	541
Pseudo R^2/R^2	0.6880	0.5775	0.3424	0.2977
LR chi^2 (12)/F	444.03	344.57	21.91	17.19

t statistics in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

between land and human resources brought about by labor migration and demographic changes. Finally, it is essential to provide well-established exit mechanisms. To rationalize the mobility of farmers and change the status of farmland abandonment, it is necessary to design exit mechanisms for land contract management rights. Legitimate exit mechanisms can help to polarize village members around farmland, provide new functions of collective management, and offer the possibility of raising villages' incomes.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Requests to access these datasets should be directed to Jie Chen, c_jie@jxau.edu.cn.

Author contributions

YX: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. GL: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft. JF: Investigation, Software, Writing – review & editing. HD: Data curation, Software, Validation, Writing – review & editing. XL: Project administration, Supervision, Writing – review & editing. CJ: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the National Natural Science Foundation of China (grant no. 42161053), Key Project of the Key Research Base for Philosophy and Social Sciences in Jiangxi Province (grant no. 23ZXSKJD07), and Jiangxi Modern Agricultural Development Collaborative Innovation Center Project (grant no. 2022-YBKT-03).

Acknowledgments

The authors appreciate the editors and reviewers for their valuable comments and suggestions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer YZ declared a shared affiliation with the authors to the handling editor at the time of review.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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