



The adoption of agroforestry practices: the determinants and constraints among smallholder farmers in Juba County, South Sudan

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Abstract Agroforestry (AF) is an integrated farming system that offers both tangible and intangible benefits. In many developing countries like South Sudan, where resources for agricultural development are limited, farmers still tend to increase their motivation to incorporate woody perennials into agroforestry practices. However, several studies have shown that socioeconomic and institutional factors play crucial roles in farmers' decision-making processes regarding agroforestry adoption. Therefore, this study aimed to identify the key factors influencing farmers' adoption decisions in Rajaf Payam, Juba County, South Sudan, by applying probit and multivariate probit regression analyses. Since different agroforestry practices may have varying impacts on farmers' adoption decisions, a multivariate probit approach ensures that these practices are analyzed simultaneously, compared to using a simple probit model applied to a binary dummy variable of each agroforestry practice separately. The data were collected from 348 randomly selected households using structured

questionnaires administered to household heads. Key informant interviews (KIIs) and focus group discussions (FGDs) were also conducted. The main findings revealed that gender, access to credit, access to quality and improved seeds, household size, distance to market, mode of farmland acquisition, extension contact, livestock ownership, and parcel size significantly affected agroforestry adoption. The study also found that common agroforestry practices included scattered trees on croplands (44.60%), homegardens (22.44%), and boundary planting (16.34%). These practices mainly involved fruit tree species such as *Mangifera indica* (26.9%), *Citrus sinensis* (15.8%), *Carica papaya* (10.1%), and *Azadirachta indica* (9.2%), which were primarily used for food provision (24.4%), shade (7.2%), and protective/windbreak purposes (6.6%). Moreover, the results indicated that the major constraints hindering adoption were a lack of low-cost, quality inputs (ranked 1st), high rates of insecurity (ranked 2nd), a lack of capital (ranked 3rd), and insufficient labour (ranked 4th). Overall, to scale up and sustainably increase adoption rates, targeted efforts to promote agroforestry interventions should be prioritized, including mobilizing and allocating more resources to these practices.

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Introduction

Agroforestry is a deliberate practice of farming systems in which woody perennials (trees, shrubs, vines, bamboo, etc.) are combined with non-woody components of crops and animals in the same piece of land, where there are economic and ecological interactions among the components in nature (Nair et al. 2021; World Agroforestry Center, 2013). Farmers' management of trees (both natural stands and plantations) on their farmlands provides private and tangible benefits to those who practice it. These benefits include income generation, food security, soil fertility, amelioration of microclimates, biodiversity habitats, water and soil conservation, etc. (Sudomo et al. 2023; Coulibaly et al. 2017; Kuyah et al. 2017; Montagnini and Metzger 2017; Obiri et al. 2011).

While these benefits are more important for resource-poor farmers in developing countries, since they tend to be food insecure and do not have many income-generating opportunities, other benefits are associated with indirect benefits related to social benefits to society, such as environmental conservation, biodiversity, carbon sequestration, water regulation, mitigating climate change, etc. (Yasin et al. 2024; Gupta et al. 2023; Handa et al. 2020; Jose 2019; Agevi et al. 2017). It is worth mentioning that in most developing and low-income countries in sub-Saharan Africa, with a rising population growth (over 80%) working in the agricultural sector, such aforementioned services are of great importance, despite not attracting much investment from government and/or private sectors (Benjamin and Sauer 2018; Meijer et al. 2015).

From the early days when the concept of agroforestry was introduced in the late 1970s, its benefits to food production and the environment have been emphasized (Swaminathan 1987). Recently, agroforestry has been gaining more attention, particularly in sub-Saharan Africa, because of increasing concerns about climate change and the sustainability of food production. For example, a review by Kpoviwanou et al. (2024) showed that the number of studies on agroforestry technology adoption in Africa increased after 2015.

Despite the high potential benefits for livelihoods and the environment, the adoption rate of agroforestry remains low in Africa. According to the review by Kpoviwanou et al. (2024), 18 of 36 papers

systematically reviewed reported the rate of non-adoption of agroforestry, which varied from 5.31% to 77%, with a mean of approximately 38%. The adoption rate of agroforestry can be enhanced by mitigating constraints, but the constraints should depend on location and the type of agroforestry. Therefore, we are urged to conduct more adoption studies to identify site- and technology-specific constraints so that appropriate policy interventions can be designed.

Our study focuses on Rajaf Payam, a peculiar agroecological area of Juba county in the Nile River Basin of South Sudan, where several different kinds of agroforestry are practiced, and the adoption rate is more than 80% if the adopter of agroforestry is defined as a household that practices at least one type of agroforestry. However, because agroforestry is not a single technology, but a group of different practices that rely on trees in our study site, this study considers the adoption of each practice, employing a multivariate probit model. Additionally, because agroforestry is heterogeneous, we examine how this heterogeneity influences farmers' adoption decisions using data from Rajaf Payam, where diverse agroforestry practices are implemented within study sites that share a similar agroecology. Although technical challenges related to agroforestry are manageable, socio-economic and institutional differences may create hindrances in individual adoption decisions. Therefore, this study aims to (i) examine the major agroforestry practices and their determinants influencing smallholder farmers' adoption decisions, and (ii) explore and identify the constraints to agroforestry practices and opportunities considered inevitable by smallholder farmers to promote the adoption of agroforestry practices. Using data collected in Juba County, South Sudan, this study attempts to answer the following research questions:

- 1) Which agroforestry practices and tree species are preferred by smallholder farmers in the study area?
- 2) Why choose agroforestry and what are its benefits for local farmers?
- 3) What factors significantly influence farmers' adoption decisions?
- 4) What are the main constraints to adoption?
- 5) What opportunities do farmers consider vital for encouraging and promoting agroforestry in the area?

Our study, therefore, analyzes and documents the influencing factors anticipated to challenge the successful adoption of agroforestry practices by smallholder farmers. This is to better understand farmers'

responses to agroforestry adoption, the barriers, and farmers' adoption strategies, which are ones currently being explored by this research, having an expansive continuum of fact-finding and discussions. Therefore, much effort should focus on awareness and education of household farmers to increase their understanding of the importance of agroforestry technologies to their livelihoods for sustainable agroforestry practices in Rajaf Payam of Juba County, South Sudan.

Literature review

Agricultural innovations, such as agroforestry practices and technologies, are essential adaptation mechanisms that enable smallholder farmers to cope with unforeseen shocks and productivity uncertainties (Jha et al. 2021). This innovation has proven to have a high impact on improving the adaptive capacity of farmers and has become a resilient system for local and traditional farming practices. Studies on the adoption of agroforestry belong to the literature on the adoption of agricultural technologies, which theoretically can be classified into three paradigms: the innovation-diffusion paradigm, the economic constraints paradigm, and the adopter-perception paradigm (Ruzzante et al. 2021). These paradigms offer valuable tools to understand how smallholder farmers can transition from traditional to modern and new agroforestry farming systems and technologies. Since farmers' socio-economic factors should be influencing their adoption decisions, this study follows the economic constraints paradigm, where farmers are assumed to maximize utility. Empirically, since utility is not observable, an observable binary dummy for the adoption is used, and a probit or a logit model is applied. Moreover, when the adoption of multiple practices/technologies is considered, multinomial logit or multivariate probit can be employed: the former is the case of mutually exclusive adoption, while the latter is the case of simultaneous adoption (Shah and Alharthi 2025).

There have been many studies on the adoption of agroforestry in sub-Saharan Africa. Amare and Darr (2020) identified 58 journal articles published between 2005 and 2019 that use econometrics to analyze socio-economic factors influencing agroforestry adoption. With respect to econometric models, they show that almost all studies use a simple binary model (either binary logit or binary probit) and that

only one paper employs a multivariate probit model. On the other hand, Kpoviwanou et al. (2024) identified 36 journal articles published between 2000 and 2023 on the adoption of agroforestry in Africa (not Sub-Saharan Africa). In terms of analytical methods, they include studies without econometrics and classify approximately 30% of the papers as employing binary logit, binary probit, or linear probability models, and approximately 7% employ a multivariate probit model.

This classification of econometric models implies that most existing studies assume "agroforestry" to be one technology that may include several different practices or analyze each agroforestry practice in a binary framework independently. An example of the former case is Tafere and Nigussie (2018), who constructed a binary dummy variable for agroforestry adoption based on four different kinds of practices, namely homegarden, woodlot, farm boundary planting, and alley planting and applied a logit model to identify the determinants of agroforestry adoption. Another example of the former case is Camara et al. (2023), who treated the practice of Farmer Managed Natural Regeneration (FMNR) as "agroforestry" and a binary dummy variable for its adoption was used as the dependent variable of a probit model. On the other hand, there are only a few studies that employ multivariate probit models. For example, Sisay et al. (2023) include "agroforestry" as one of the climate-smart technologies and simultaneously estimate multiple probit equations. However, in their model, agroforestry is only one of the technologies, and others are crop diversification, integrated soil fertility management, small-scale irrigation, etc. However, the authors could not find any papers that apply a multivariate probit model to explain differences in factors influencing different agroforestry technologies, although such models are often used in other fields of technology adoption (e.g. Shah and Alharthi, 2025; Tanti and Jena 2023). Therefore, our approach that applies a multivariate probit model to several different practices of agroforestry is relatively new and will have some novelty.

As mentioned above, the adoption rate of agroforestry varies a lot (Kpoviwanou et al. 2024), and almost all the studies on agroforestry adoption aim to identify factors influencing the adoption. Such factors include not only technical/physical ones but also socioeconomic and institutional ones (Jha et al.

2021; Binam et al. 2017; Owombo and Idumah 2017; Oli et al. 2015; Zerihun et al. 2014). According to Tranchina et al. (2024), who reviewed systematically 90 studies on agroforestry adoption globally, out of which 27 are the cases in Africa, product marketing, knowledge/experience, and labor requirement are the most frequently mentioned socioeconomic constraints, while land tenure is the most frequently mentioned institutional constraint in Africa. However, their frequencies are less than 30%. On the other hand, the availability of land space, water, and seeds/seedlings is the major technical constraint with more than 30% frequency. Compared with other regions such as Asia, Europe, and North America given in Tranchina et al. (2024), the constraints in Africa are much less concentrated. We imagine that agroforestry in Africa is more diverse than in other regions, and as a result, the constraints are also diverse. One of the reasons behind it will be that agroforestry in Africa contains several different practices, which may have different influencing factors. For example, homegarden and woodlot consist of the binary dummy variable for agroforestry, but their determinants cannot be the same. Based on this consideration, our approach that employs a multivariate probit model can be justified. Therefore, this review aims to establish a foundation for theory related to adopting new technologies like agroforestry by examining important factors, concepts, and frameworks from existing literature that provide valuable insights into how smallholder farmers adopt agroforestry technology(ies). Applying these theoretical concepts to our study can help develop more effective empirical models and strategies to promote sustainable agroforestry practices, which can strengthen the resilience of farming communities against shocks.

Materials and methods

Description of the study area

This study was conducted in the four villages (called Bomas) of Rajaf Payam, namely, Kolye East, Kolye West, Gumbo, and Tokiman Islands. Rajaf is part of the hills and mountain agroecological zone of Central Equatoria State, South Sudan. It is one of the 13 payams of Juba County. It is about 10–13 km south of Juba City, located along the eastern and western

banks of the River Nile, at 460 m above sea level. The study area stretches from Rajaf Center to about 5 km to Tokiman, 7 km to Gumbo center, 15 km to Kolye East, and approximately 25–30 km to Kolye West. It is situated at a latitude range between 4° and 6° North and has a longitude range of 27° and 32° East (Fig. 1). Its area covers a total of about 3,204 km² with an estimated population of about 15,604 people. This population has, however, doubled to approximately 31,000 due to a high influx of internally displaced people (IDPs) and returnees from the neighboring states and counties affected by the 2013 and 2016 escalated conflicts (Mayele and Bongo 2022). This group category was not included in the sample.

Rajaf exhibits a tropical rainy and dry climatic atmosphere, with high temperatures all year round because it is situated close to the equator. It has a mean temperature ranging between 30–33 °C in the dry season, which usually drops to 18 °C in the wet season (Donat et al. 2014). The highest temperature of 38 °C is usually witnessed in February, with the hottest being experienced between November and March. The mean annual rainfall of approximately 1200 mm, concentrated during the rainy season between April and November (Fig. 2). The area is accustomed to seasonal flooding and increased evaporation due to its proximity to the Nile River. Humidity usually exceeds 80% during the rainy season and drops to below 50% in the dry season (Alrajoula et al. 2016; Mohamed, 2007). The area is characterized by an alluvial geological formation consisting of vetric soils. These alkaline soils have low organic matter content, high salinity, and 15 to 40% clay content mixed with clay loams, brownish in morphology, a characteristic of both the green belt and hills and mountains agroecological zones of South Sudan (Mayele and Bongo 2022).

Rajaf is inhabited mainly by the Bari tribe, about 90% of the agrarian population, with farming as its main economic activity. Other small-scale economic activities include livestock rearing, fishing, firewood collection, and charcoal burning. This area has become an important site for fishing in the state due to its proximity to the shores of the Nile River, which also favors agriculture, agroforestry practices, and natural forest stands because of its fertile soil grades. The major food crops cultivated include sorghum, cassava, maize, groundnuts, sesame, beans, sweet

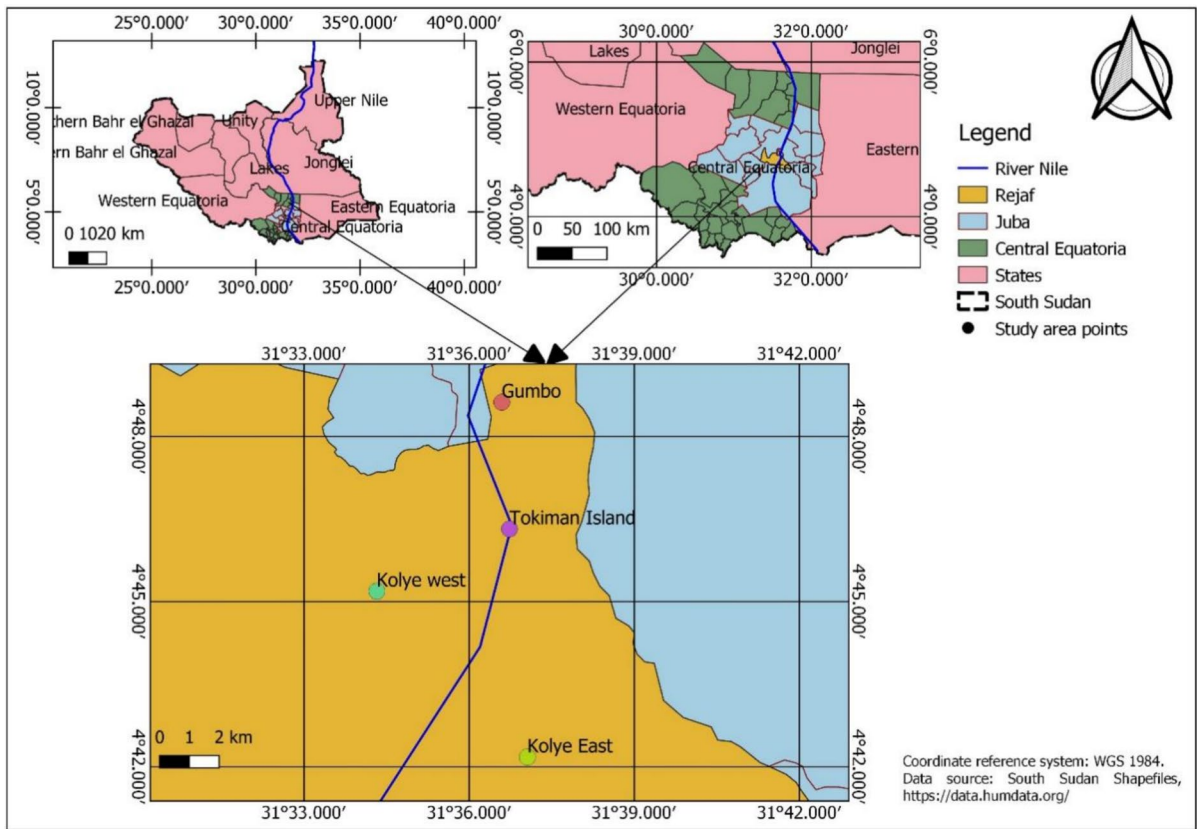


Fig. 1 The map showing the location of the study area (Source: primary data)

potatoes, etc., while most green vegetables are sparingly grown as cash crops to meet market demands. The main livestock kept are goats, sheep, pigs, chickens, and guinea fowl, with a few households that rear cattle.

The common native agroforestry tree species found in the study area include *Tamarindus indica*, *Balanites aegyptica*, *Borassus aethiopum*, *Acacia nilotica*, *Acacia seyal*, *Kigelia africana*, etc., while exotic species include *Mangifera indica*, *Citrus sinensis/limon*, *Carica papaya*, *Psidium guajava*, *Azadirachta indica*, *Eucalyptus camaldulensis*, *Tectona grandis*, *Senna siamea*, *Moringa oleifera*, etc. (Mayele and Bongo 2022).

Research design, sample size, and sampling procedure

This study was a descriptive cross-sectional approach involving household surveys and on-farm observation. The study adopted a multi-stage sampling technique to select sample households. In the first stage, Rajaf Payam was purposefully selected for the study from the thirteen payams of Juba County because it is among the areas with the presence of agroforestry practices within the region. The second stage involved the selection of four key villages (also known as Bomas) of Rajaf Payam, including Kolye East, Kolye West, Gumbo, and Tokiman, with their potential site coverage of agroforestry activities and advantage to the use of River Nile water for distinct AF species, as well as the availability and representativeness of varying agroforestry practices. The third stage involved the

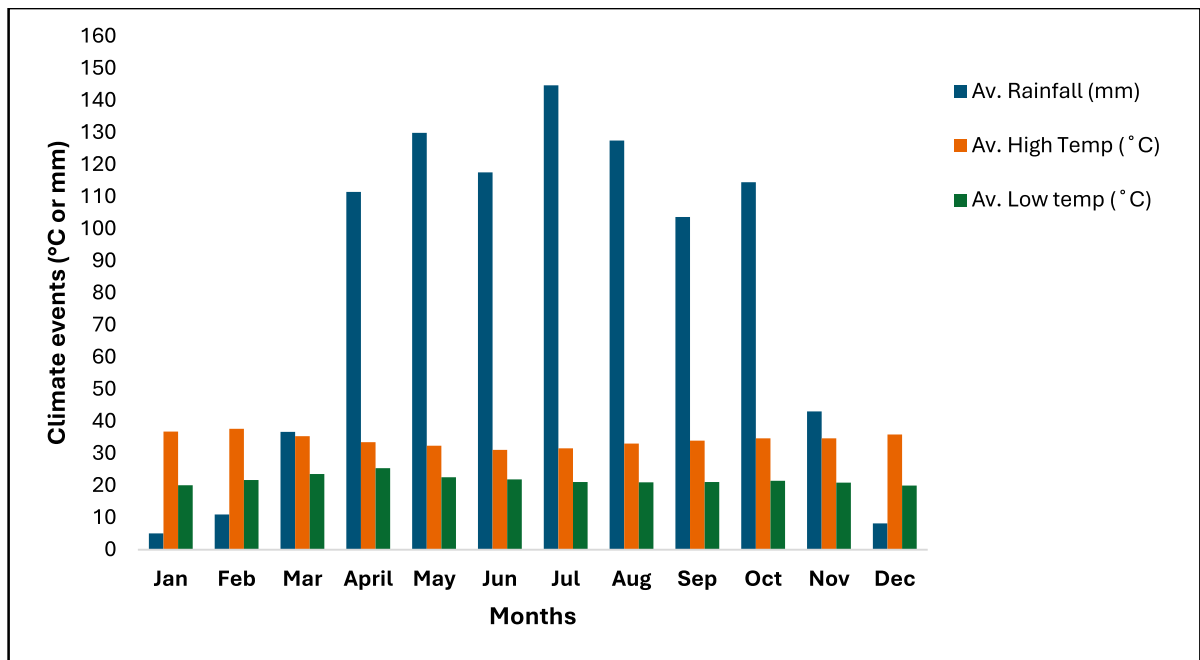


Fig. 2 The average amount of rainfall and temperatures experienced in Rajaf Payam (Source: Gore et al., 2021)

random selection of sample households in the four selected villages.

The sample size was computed from the following Yamane (1967) formula:

$$n = \frac{N}{1 + N(e)^2} \quad (1)$$

where n =the desired sample size (that is, if the target population is greater than 10,000 people), N =the estimate of the target population size, e =the level of statistical significance (maximum tolerable error, at 95% level of confidence), usually set at 5% or 0.05. Since the estimated population of Rajaf Payam is 31,000, the desired sample size is obtained as:

$$\text{Sample size}(n) = \frac{31,000}{1 + 31,000(0.05)^2} = 395.$$

Following this calculation, at least 98 households from each village were randomly selected and interviewed. Finally, a total of 395 households were interviewed in the 4 villages. However, after data cleaning, only 348 formed the total sample for the analysis.

Data collection and instrumentation

Before data collection, a reconnaissance survey was conducted to give the overall baseline overview and information regarding the study area, different farmers or farmers' groups, key agroforestry practices, people's cultures, access roads, and people's perceptions towards the survey (see Appendix Table 10). The data collection was conducted from November 2023 to April 2024 by four well-trained enumerators using structured field questionnaires, which were first subjected to pre-testing for 16 household respondents, at least 3 from each selected village.

The survey focused on the respondents' socio-economic, demographic, and institutional factors hypothesized to influence the household decision to adopt or not adopt agroforestry practices (Obiri et al. 2011). All interviews were conducted in the local language (Bari dialect), including Arabic. This was for easy understanding and filling out of the questionnaires to avoid misinterpretation, but the final responses were recorded in English by enumerators. Note that the sample households were randomly selected in each village; the sample includes both the adopters of

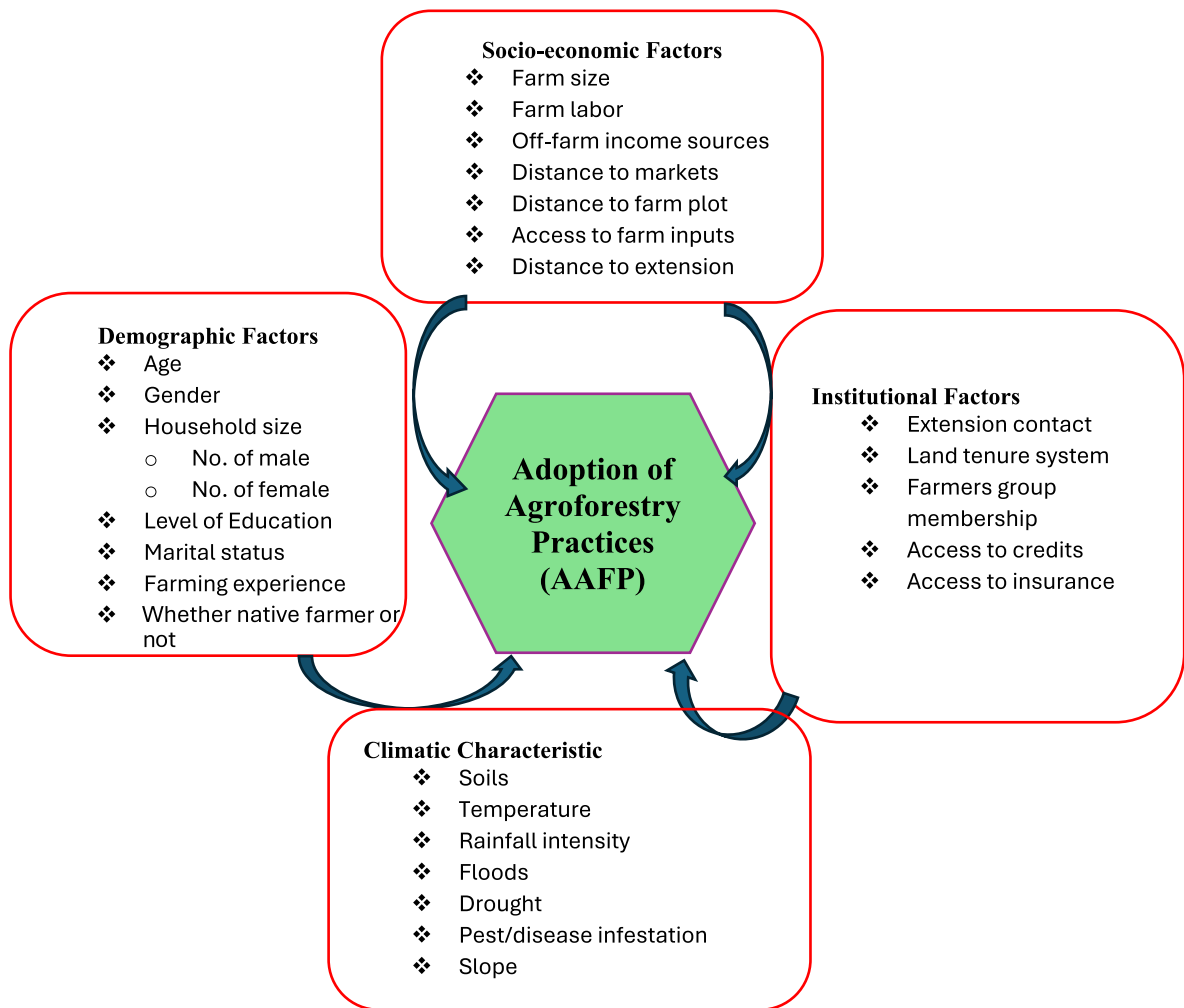


Fig. 3 Conceptual Framework for Determinants of Adoption of Agroforestry Practices by Smallholder Farmers (Source: Author, 2025)

agroforestry and non-adopters (290 adopters and 58 non-adopters).

In addition to the household interviews, our study held 4 FGDs, one from each study location, comprising both men and women of diverse age categories separately. Additionally, 16 checklists (4 for each study location) were also administered to KIIs who were purposefully chosen from relevant government institutions, community leadership, local agroforestry initiatives, community extension workers, community-based organizations, community youths organizations, farmers groups, and any residents working for non-governmental organizations (NGOs) because they have knowledge of agroforestry farming

practices in the study area and can provide specific information that is relevant to the study.

The household head or any of its willing representatives aged 17 and above present was interviewed. This category of household representatives includes the wife, the children of the household head, relatives, and workers who are presumed to have lived with the household head for at least two years, having knowledge and experience of the household's farm activities. However, the category of workers was removed from the sample because they had been hired, thus reducing the sample size to 348.

Broadly, our study integrates and discusses the influence of a spectrum of household variables that

include demographic, socioeconomic, institutional, as well as farm characteristics shown in the following integrated conceptual framework (Fig. 3). It identified numerous factors anticipated to both positively and negatively affect agroforestry practices as fundamental to understanding the adoption decisions of smallholder farmers. It emphasized a mix of both observable and unobservable factors that influence the adoption process of agroforestry. The observable variables are construed as independent variables encompassing diverse farmers' perceptions including demographics (age, gender, marital status, education levels, household size, dependence ratio, etc.); socio-economic and farm variables (farm size, farm labor, distance to market, farming experience, off-farm income sources, distance to farm plot, access to farm inputs, etc.); institutional characteristics (e.g. access to credits, land tenure systems, extension agent contact), and climatic characteristics (temperature, rainfall, floods, drought, soils, slope, etc.). Whereas unobservable variables are factors that may affect treatment (Agroforestry adoption) and outcome variables (Practices), and are captured by the error term in the probit computation, which portrays farmers' adoption decisions, innate abilities, motivation, risk perceptions, and other similar factors.

It also provides a comprehensive insight and analysis of the key variables, offering a structured approach to adoption decisions and their impacts. Furthermore, our integrated conceptual framework (Fig. 3) does not only underscores the hypothesized associations between socioeconomic factors, agroforestry adoption, and practices, but it also highlights and includes the major factors (climate change) influencing agroforestry adoption by smallholder farmers. It can therefore be emphasized that these factors collectively enhanced the shaping of the landscape for agroforestry adoption.

We then define *agroforestry adoption* as the uptake of one or more practices (adoption status) by farmers who have resided in the study area for a long time, preferably, 5 years or above, and have either deliberately left, retained, or planted specific woody perennial species on their farmlands. We further employed a household approach to agroforestry adoption, operationalizing adoption in terms of farmers' species preferences, the combination of agroforestry practices within each community, and the number of trees per community. *Agroforestry practice* is therefore defined

as a management operation in an AF system or simply the arrangement of AF components in space and time for various roles. However, due to the distinct functions of agroforestry, the study defines the surveyed agroforestry practices as follows: Scattered trees on cropland (SCL) as trees planted or retained on cultivated cropland for specific purposes; homegardens (HG) as tree planting or retention around homestead including livestock niches and those surrounding the compound for aesthetic and protective roles (mostly shade and fruit trees); boundary planting (BP) as tree species planted on the plot boundary to demarcate borders, protection or as live fences as well as rows of trees separating different practices within the farm; woodlots (WL) as planting or retention of numerous species in a stand, mostly as monocrops although it may be in combinations, mainly for timber, fuelwood, and food production; and alley cropping (AC) agroforestry practice defined as tree species planted to form alleys or a row within cultivated crops on farmland.

Empirical model selection and data analysis

Based on the reconnaissance survey, we identified the above 5 agroforestry practices that a significant number of sample farmers had adopted. Then, we define that the farmer is an "agroforestry adopter" if he/she adopt at least one of the five agroforestry practices. In addition, since the motivation to adopt the five agroforestry practices and their effects on crop production may not be equal, we consider the adoption of each practice separately. Using a binary dummy variable for the adoption of each practice, this study employs a probit regression model (Eq. 2) and a multivariate probit regression model (Eq. 3) to identify factors associated with the adoption of agroforestry. The multivariate probit regression (MVP) model allows the cases where a farmer chooses more than one agroforestry practice, unlike multinomial probit regression models that require a mutually exclusive assumption on the binary choices (Mittal and Mehar 2016; Jenkins et al. 2011).

The following probit regression model formula was used in the case of agroforestry adoption:

$$AFAdopt_i = X_i\beta + \varepsilon_i \quad (2)$$

where $AFAdopt_i$ is a binary dummy variable that equals 1 if farmer i adopts at least one of the 5 agroforestry practices, and 0 otherwise, for non-adopters; X_i represents independent variables of demographic, socioeconomic, and institutional factors (potentially) associated with the adoption of agroforestry; β represents parameters to be estimated of independent variables whose association with the likelihood of agroforestry adoption is assessed; and ε_i , the error term. The multivariate probit regression model for the analysis of 5 agroforestry practices is given below.

$$Y_{ij} = X_{ij}\delta_j + \varepsilon_{ij} \quad (3)$$

where i is the index of farmer and j is the index of type of agroforestry: 1 = scattered trees, 2 = homegarden, 3 = boundary planting, 4 = woodlot, and 5 = alley cropping; Y_{ij} is a binary dummy variable taking 1 if farmer i adopts j^{th} agroforestry and 0 otherwise; X_{ij} represents independent variables of demographic, socioeconomic, and institutional factors (potentially) associated with the adoption of agroforestry; δ_j represents parameters to be estimated of independent variables whose association with the likelihood of j^{th} agroforestry adoption is assessed; and ε_{ij} is the error term. Assuming the error terms are correlated across j , Eq. 3 is estimated using simulated maximum likelihood. The explanatory variables for adoption and description of farmers' socio-economic characteristics are presented in the following Table 1.

Results and discussion

Summary of descriptive statistics of respondents' characteristics

Results show that over 80% and 18% were male and female household respondents, respectively (Table 2). The average age of household heads was approximately 40 years, indicating that it is within a productive and active category of farmers who are more likely to adopt agroforestry practices than older farmers. Older farmers are highly regarded as unproductive in modern farming systems, especially as they tend to view agroforestry practices as time-consuming and labor-intensive technologies, yet they require a substantial amount of effort to relinquish. Over 65% of household heads were native farmers, whilst

the remaining 33% were migrant settlers, and over 75% of them were married, with about 15 years for an average experienced farmer, yet a few household heads (27%) attained formal education (Table 2). It is nonetheless said that a significant proportion of these few well-educated family members often migrate to major towns and cities in search of *greener pastures* and access to white-collar jobs other than farming, thus fluctuating literacy levels and leaving the rural areas dominated by those with low literacy levels.

The average household size was approximately 5 members (Table 2). This is considered slightly lower than the national estimated average of 6 people per household, according to statistical repository data registered for South Sudan from the Sudan Housing and Population Census, 2008. The households had an average farm size of approximately 2 ha per household. It can be hinted that farmers with smaller parcels of land are more likely to adopt agroforestry because of their ability to accommodate all the agroforestry components in their meagre plots. Yet farmers' adoption of larger agroforestry practices often had the experience of economies of scale that allowed them to save costs, receive both tangible and non-tangible benefits, and develop and improve their infrastructure, thus increasing their farm profitability as well as lowering their production expenditures. 55% of household farmers had acquired land through varied means such as inheritance and long-term leasehold, with an estimated 3 km average distance to their farm plots. The average distance to markets was estimated at 6 km, and most household farmers had low access to extension centers for extension services, with less frequency of agent contacts (35%), and low credit access (10%). Over 40% households had access to improved seeds and owned livestock, while engaged in off-farm income activities (Table 2). Further results show that 81% of households have experience with rainfed agroforestry. Other sources of water for agroforestry practices accounted for less than 20%, with the use of loamy and clay soils accounting for over 90% responses, most preferred in moderate slope (6–20%) gradient, accounting for 34% (Table 2).

Mean comparison of characteristics of Agroforestry adopters and non-adopters

An independent two-sample t-test was computed to compare the relationship between the adopters and non-adopters of agroforestry practices with the socio-economic characteristics influencing their decisions.

Table 1 Description of the explanatory variables of the study

Variable	Explanatory variable descriptions
Household/respondent characteristics	
Female-headed household	Binary/dummy: 1 if female-headed household, and 0 otherwise
Age	Continuous: The respondent's age in years
Marital status	Binary/dummy: 1 if the respondent is married, and 0 otherwise
Native farmer	Binary/dummy: 1 if the respondent's family is native, and 0 otherwise
Years of farming experience	Continuous: respondent's number of years in farming
Educational status	Binary/dummy: 1 if the respondent is educated, and 0 otherwise
HH size	Continuous: Total number of household members
Household plot characteristics	
Farm size	Continuous: The size of the farm in hectares
Size of the parcel/plot	Continuous: The size of the parcel/plot in hectares
Distance to farm plot	Continuous: distance from the HH to the farm plot (km)
Mode of farmland acquisition	Binary/dummy: 1 if through inheritance, 0 otherwise
Land tenure system	
Owned family land	Binary/dummy: 1 if yes, 0 no
Allocated family land	Binary/dummy: 1 if yes, 0 no
Rented-in/Lease land	Binary/dummy: 1 if yes, 0 no
Community land	Binary/dummy: 1 if yes, 0 no
Government allocated	Binary/dummy: 1 if yes, 0 no
Water source	
Rain-fed	Binary/dummy: 1 if yes, 0 no
Flood water from river/swamp	Binary/dummy: 1 if yes, 0 no
Diversion from river water	Binary/dummy: 1 if yes, 0 no
Soil Type	
Loamy soil	Binary/dummy: 1 if yes, 0 no
Clay soil	Binary/dummy: 1 if yes, 0 no
Parcel Slope	
Moderate slope (%)	Binary/dummy: 1 if yes, 0 no
Steep slope (%)	Binary/dummy: 1 if yes, 0 no
Distance from the Nile to the plot	
Plot in Kolye East village	Continuous: distance from the Nile to the plot (km)
Plot in Kolye West village	Continuous: distance from the Nile to the plot (km)
Plot in Gumbo village	Continuous: distance from the Nile to the plot (km)
Plot in Tokiman Island village	Continuous: distance from the Nile to the plot (km)
Households Socio-economic & Institutional Characteristics	
HH access to credit	Binary/dummy: 1 if have access to credit or loans, and 0 otherwise
HH access to improved seeds	Binary/dummy: 1 if have access to improved seeds, and 0 otherwise
Distance to Markets	Continuous: The distance of HH to product markets (km)
Off-farm income sources	Binary/dummy: 1 if engaged in off-farm employment, and 0 otherwise
Extension/Agent contact	Binary/dummy: 1 if yes, and 0 otherwise
HH own animals/poultry	Binary/dummy: 1 if own animals/poultry, and 0 otherwise

Source: survey data, 2024

Table 2 Descriptive statistics of the household characteristics *Source: survey data, 2024*

Household characteristics	N	Mean	SD	Min	Max
Female-headed	348	0.18	0.39	0	1
Age of household heads	348	39.53	13.99	17	75
Marital status	348	0.77	0.42	0	1
If the HH head is a native farmer	348	0.67	0.47	0	1
Years of farming experience	348	14.80	13.41	0.5	70
Education status	348	0.27	0.45	0	1
HHSIZE	348	4.70	2.52	1	17
Farm size	348	2.33	2.08	0	15
Distance to farm plot	348	2.60	3.11	0	20
Mode of farmland acquisition	348	0.55	0.50	0	1
Size of the parcel/plot	348	2.30	2.00	0	15
Tenure1 (Owned family land)	348	0.45	0.50	0	1
Tenure2 (Allocated family land)	348	0.17	0.37	0	1
Tenure3 (Rented-in/Lease land)	348	0.10	0.30	0	1
Tenure4 (Community land)	348	0.16	0.37	0	1
Tenure5 (Government allocated)	348	0.02	0.14	0	1
water1 (rain-fed)	348	0.81	0.40	0	1
water2 (flood water from river/swamps)	348	0.03	0.18	0	1
water3 (diversion from river water)	348	0.04	0.20	0	1
Soil2 (Loamy soil)	348	0.49	0.50	0	1
Soil3 (Clay soil)	348	0.45	0.50	0	1
Slope2 (Moderate slope (6–20%))	348	0.34	0.48	0	1
Slope3 (Steep slope (> 21%))	348	0.06	0.23	0	1
Distance from the Nile to plot in Kolye East	348	0.38	0.65	0	1.5
Distance from the Nile to plot in Kolye West	348	0.19	0.38	0	1.5
Distance from the Nile to plot in Gumbo	348	0.16	0.25	0	0.8
Distance from the Nile to plot in Tokiman Island	348	0.04	0.10	0	0.5
HH access to credit	348	0.10	0.29	0	1
HH access to improved seeds	348	0.44	0.50	0	1
Distance to Markets	348	5.91	3.58	0	15
Off-farm income sources	348	0.43	0.50	0	1
Extension/Agent contact	348	0.35	0.48	0	1
HH own animals/poultry	348	0.41	0.49	0	1

The results show a positive and significant relationship between off-farm income sources and tenure 2 (allocated family land) with both adopters and non-adopters (Table 3). The findings indicate that a unit increase in off-farm income sources would increase the likelihood of adoption by 41% and non-adoption by 55%. On the other hand, a unit increase in land tenure system 2 (allocated family land) would increase by 18% and 9% for adopters and non-adopters, respectively. This result is not surprising, as there is a likelihood that adopters are more likely to invest part of their off-farm incomes from other sources to boost

agroforestry, while most households tend to continue to be non-adopters because they may obtain most of their basic household needs using incomes from off-farm sources, compared to the practice of agroforestry. An increase in non-adoption could be attributed to the high wages earned from off-farm income sources. *Ceteris paribus*, the results depict that adopters allocated family land are twice as high as non-adopters. This indicates that the higher the number of farmers with such a land tenure system, the more likely they are to increase agroforestry adoption. The reverse is true with the low tenure for non-adopters.

Table 3 Mean comparison of agroforestry adopters and non-adopters using two-sample t-test with equal variances of household respondents (N = 348)

Household characteristics	Mean1 (Non-adopters)	Mean2 (adopters)	Diff	St Err	t value	p value
Female-headed household	0.14	0.19	−0.05	0.06	−0.95	0.35
Age	39.62	39.51	0.11	2.02	0.05	0.96
Marital status	0.78	0.77	0.01	0.06	0.10	0.91
Native farmer	0.69	0.67	0.02	0.07	0.35	0.72
Years of farming experience	15.21	14.72	0.49	1.93	0.25	0.80
Educational status	0.35	0.26	0.09	0.06	1.35	0.18
HH size	4.38	4.76	−0.38	0.36	−1.05	0.29
Farm size	2.20	2.35	−0.16	0.30	−0.50	0.61
Distance to farm plot	2.67	2.59	0.08	0.45	0.20	0.86
Mode of farmland acquisition	0.50	0.56	−0.06	0.07	−0.85	0.39
Size of the parcel/plot	2.27	2.30	−0.04	0.29	−0.10	0.90
Tenure1 (Owned family land)	0.50	0.45	0.06	0.07	0.75	0.44
Tenure2 (Allocated family land)	0.09	0.18	−0.10	0.05	−1.80	0.07*
Tenure3 (Rented-in/Lease land)	0.14	0.09	0.05	0.04	1.15	0.26
Tenure4 (Community land)	0.12	0.17	−0.05	0.05	−0.85	0.40
Tenure5 (Government allocated)	0.02	0.02	0.00	0.02	−0.15	0.87
water1 (rain-fed)	0.81	0.80	0.01	0.06	0.10	0.90
water2 (flood water from river/swamps)	0.05	0.03	0.02	0.03	0.80	0.43
water3 (diversion from river water)	0.04	0.04	−0.01	0.03	−0.25	0.81
Soil2 (Loamy soil)	0.43	0.51	−0.08	0.07	−1.05	0.29
Soil3 (Clay soil)	0.50	0.44	0.06	0.07	0.80	0.41
Slope2 (Moderate slope (6–20%))	0.38	0.34	0.05	0.07	0.65	0.51
Slope3 (Steep slope (> 21%))	0.05	0.06	−0.01	0.03	−0.20	0.84
Distance from the Nile to plot in Kolye East	0.45	0.37	0.07	0.09	0.80	0.43
Distance from the Nile to plot in Kolye West	0.11	0.20	−0.09	0.06	−1.65	0.10
Distance from the Nile to plot in Gumbo	0.18	0.16	0.02	0.04	0.60	0.54
Distance from the Nile to plot in Tokiman	0.02	0.04	−0.01	0.01	−1.00	0.32
HH access to credit	0.05	0.10	−0.05	0.04	−1.25	0.22
HH access to improved seeds	0.41	0.44	−0.03	0.07	−0.40	0.70
Distance to Markets	6.09	5.87	0.22	0.52	0.40	0.67
Off-farm income sources	0.55	0.41	0.15	0.07	2.05	0.04**
Extension/Agent contact	0.40	0.34	0.06	0.07	0.80	0.42
HH owns animals/poultry	0.48	0.39	0.09	0.07	1.25	0.21

*** Significant at 1%; ** significant at 5%; * significant at 10%

Adoption Rates of the Major Agroforestry Practices in Rajaf Payam

The findings (Table 4) indicate that the agroforestry practices adopted by most households were SCL (44.60%), followed by HG (22.44%) and BP (16.34%). These results are consistent with the findings of Tega and Bojago (2024), who found

similar adoption rates of agroforestry practices in their study conducted in the Sodo Zuriya district of southern Ethiopia. The high adoption rates of SCL might be attributed to household farmers' tree species selection decisions, planting and retention strategies, with prospects for the continuous growth of economically and ecologically important

Table 4 Adoption rates of major Agroforestry practices among the study communities

	Name of payam					
	AF Practice	Kolye east N (%)	Kolye west N (%)	Gumbo N (%)	Tokiman Island N (%)	Total N (%)
Agroforestry practices:	SCL	40 (40.82)	18 (25.71)	64 (59.26)	39 (45.88)	161 (44.60)
SCL= Scattered trees on Cropland;	HG	15 (15.31)	19 (27.14)	33 (30.56)	14 (16.47)	81 (22.44)
HG = Homegarden;	BP	12 (12.24)	23 (32.86)	4 (3.70)	20 (23.53)	59 (16.34)
WL = Woodlots;	WL	22 (22.45)	6 (8.57)	2 (1.85)	7 (8.24)	37 (10.25)
BP = Boundary planting;	AC	9 (9.18)	4 (5.71)	5 (4.63)	5 (5.88)	23 (6.37)
and AC = Alley cropping	Total N (%)	98 (27.15)	70 (19.39)	108 (29.92)	85 (23.55)	361 (100)

agroforestry tree species on the farm. Moreover, the notion that trees sparsely dispersed in cropland do not shade understory crops may have facilitated the adoption of this practice by most farmers. Further results show that higher adoption rates of agroforestry were observed in the Gumbo site for both SCL (59.26%) and HG (30.56%), compared to the other study sites (Table 4). A higher adoption rate of agroforestry for BP was observed in Kolye West (32.86%), followed by Tokiman (23.53%) among households. These households plant trees at the border of their farms for various reasons given by key informants, including resolving border disputes among neighboring farmers, use for live fences, demarcating farm boundaries, high cost of barbed wire for fencing, and using products for cut-and-carry for livestock fodder. Most households in Kolye East (over 40%) adopted SCL, followed by the adoption of WL (22.45%) practices (Table 4). Overall, the study found that over 80% of household farmers were adopters of agroforestry practices. This conforms to the survey conducted by Kinyili et al.(2020), who also found that over 80% of household farmers adopt agroforestry practices in a similar study. Yet, studies conducted by Makori (2017) and Maluki et al.(2016) are contradictory to our current findings. Unsurprisingly, our results suggest that the semi-arid and dryland regions like Rajaf of South Sudan may encourage farmers to adopt various agroforestry practices that would contribute to providing their ecosystem services and improving rural livelihoods. Our findings, therefore, indicate that most household farmers adopted the practice of SCL, HG, and BP, which corroborates with other previous studies

(Tega and Bojago 2024; Alemayehu and Simeneh 2024). Additionally, our study also agrees with other studies by Kuyah et al. (2020) and Lasco et al.(2014), who reiterated that several farmers preferred BP to provide shelters, prevent frosts, and act as windbreaks, as well as demarcate boundaries to avoid land disputes and trespassers, also argued by Kinyili et al.(2020). Nevertheless, AC was found to be the least commonly adopted agroforestry practice by the household farmers in the study area(Table 4).

Woody perennial species and their benefits influencing households' decision to adopt agroforestry

The results indicate that 14 important woody perennial species were incorporated into various agroforestry practices in the surveyed sites. Their botanical family and common names are presented in Appendix Table 11. The top-ranked dominant species that highly influenced households' preference to practice agroforestry were mostly fruit trees, which include *Mangifera indica* (26.91%), *Citrus sinensis* (15.84%), *Carica papaya* (10.11%), *Azadirachta indica* (9.16%), *Tectona grandis* (7.25%), and *Psidium guajava* (5.15%). A few others are practiced on a small scale (Table 5). The majority of household heads reported more tree species (48.34%) with species richness (12) for Tokiman Island compared to the other study locations. Kolye West has the lowest species richness (8), although with a somewhat high species abundance (25.54%)(Table 5). Farmers' preference was because of the species' multiple and distinct uses, including provision of food, shade, protective (windbreaks, live fences, aesthetics, etc.),

Table 5 Top dominant woody perennial species preferred within the agroforestry study sites

Tree species name	Name of sample payam				Total		
	Kolye East	Kolye West	Gumbo	Tokiman	Fr	%	Ranking
<i>Mangifera indica</i>	16	54	14	57	141	26.91	1st
<i>Citrus sinensis</i>	0	17	0	66	83	15.84	2nd
<i>Carica papaya</i>	1	1	0	51	53	10.11	3rd
<i>Azadirachta indica</i>	12	25	9	2	48	9.16	4th
<i>Tectona grandis</i>	13	10	4	11	38	7.25	5th
<i>Psidium guajava</i>	5	15	3	4	27	5.15	6th
<i>Gmelina arborea</i>	17	0	7	0	24	4.58	7th
<i>Ficus benjamina</i>	5	5	2	6	18	3.44	8th
<i>Trichilia hirta</i>	0	0	4	13	17	3.24	9th
<i>Annona squamosa</i>	0	0	0	17	17	3.24	9th
<i>Senna siamea</i>	1	0	8	7	16	3.05	11th
<i>Pithecellobium dulce</i>	0	0	3	11	14	2.67	12th
<i>Tephrosia vogelii</i>	2	4	0	3	9	1.72	13th
<i>Buxus sinica</i>	0	0	8	0	8	1.53	14th
Total N (%)	72 (14.04)	131 (25.54)	62 (12.09)	248 (48.34)	513 (100)	100	

Table 6 Proportional ranking of the benefits of woody perennial species in agroforestry

What are the trees used for?	Frequency	percentage	Ranking
Provide fruits, leaves, seeds, and nuts for food	85	24.43	1st
Food and Shade	36	10.34	Mixed
Food and Building	35	10.06	Mixed
Food, Firewood & shade	26	7.47	Mixed
Provide shade	25	7.18	2nd
Protective (windbreaks, live fences, aesthetics, etc.)	23	6.61	3rd
Both food and sales	22	6.32	Mixed
Building material	17	4.89	4th
Provide fodder for livestock	14	4.02	5th
Fertilize the soil	10	2.87	6th
Use as fuelwood	10	2.87	6th
For market to generate incomes	10	2.87	6th
Others (perfumes, poison, insecticides,	10	2.87	Mixed
Firewood and Shade	9	2.59	Mixed
Eradicate climate change	7	2.01	9th
Fodder and shade	7	2.01	Mixed
Medicinal/herbs	2	0.57	10th
Total	348	100	

Mixed = shared function/
uses

construction materials, livestock fodder, and others (Table 6; Appendix Table 12). The study results align with those of Mukhlis et al. (2022), who reiterated that households were influenced to plant or retain different tree species due to their distinct uses. Indeed, the ideal nature and function of these retained or

planted trees and shrubs in any agroforestry practice should focus on multipurpose species that encompass all the above benefits, including their contribution to climate change mitigation and income generation (Alemayehu and Simeneh 2024).

Socioeconomic and institutional factors influencing the adoption of agroforestry by smallholder farmers

Our study employs a probit empirical model to

examine the impact of various demographic, socio-economic, institutional, and climatic characteristics on the adoption of agroforestry practices by smallholder household farmers. This model is chosen for

Table 7 Socioeconomic and institutional factors influencing adoption of agroforestry by smallholder household farmers using the Probit Regression Model (N = 348)

ADOPTAF	Coef	St Err	t-value	p-value	[95% Conf Interval]		Sig
Female-headed household	0.449	0.285	1.570	0.116	−0.111	1.008	
Age	0.001	0.008	0.200	0.845	−0.014	0.017	
Marital status	−0.071	0.228	−0.310	0.755	−0.519	0.377	
Native farmer	−0.163	0.237	−0.690	0.490	−0.627	0.301	
Years of farming experience	−0.003	0.009	−0.380	0.707	−0.021	0.014	
Educational status	−0.220	0.192	−1.150	0.251	−0.595	0.155	
HH size	0.046	0.035	1.340	0.181	−0.022	0.114	
Farm size	0.046	0.073	0.620	0.533	−0.098	0.190	
Distance to farm plot	−0.004	0.037	−0.110	0.915	−0.077	0.069	
Mode of farmland acquisition	0.585	0.323	1.810	0.070	−0.048	1.217	*
Size of the parcel/plot	−0.017	0.075	−0.230	0.821	−0.163	0.129	
Tenure1 (Owned family land)	−0.247	0.454	−0.540	0.587	−1.137	0.644	
Tenure2 (Allocated family land)	0.525	0.399	1.310	0.189	−0.258	1.307	
Tenure3 (Rented-in/Lease land)	−0.001	0.416	0.000	0.998	−0.817	0.815	
Tenure4 (Community land)	0.283	0.445	0.640	0.524	−0.589	1.155	
Tenure5 (Government allocated)	0.156	0.749	0.210	0.835	−1.312	1.625	
water1 (rain-fed)	−0.106	0.272	−0.390	0.696	−0.640	0.427	
water2 (flood water from river/swamps)	−0.524	0.525	−1.000	0.318	−1.554	0.505	
water3 (diversion from river water)	0.259	0.558	0.460	0.643	−0.835	1.353	
Soil2 (Loamy soil)	0.092	0.400	0.230	0.819	−0.692	0.876	
Soil3 (Clay soil)	−0.158	0.397	−0.400	0.690	−0.936	0.619	
Slope2 (Moderate slope (6–20%))	−0.125	0.191	−0.650	0.513	−0.499	0.249	
Slope3 (Steep slope (> 21%))	0.065	0.430	0.150	0.881	−0.778	0.907	
Distance from the Nile to plot in Kolye East	0.038	0.201	0.190	0.851	−0.356	0.432	
Distance from the Nile to plot in Kolye West	0.837	0.365	2.290	0.022	0.122	1.553	**
Distance from the Nile to plot in Gumbo	−0.082	0.692	−0.120	0.906	−1.438	1.274	
Distance from the Nile to plot in Tokiman	2.227	1.534	1.450	0.147	−0.781	5.234	
HH access to credit	0.726	0.339	2.140	0.032	0.062	1.390	**
HH access to improved seeds	0.149	0.201	0.740	0.458	−0.245	0.542	
Distance to Markets	−0.048	0.031	−1.540	0.123	−0.110	0.013	
Off-farm income sources	−0.232	0.187	−1.240	0.214	−0.599	0.134	
Extension/Agent contact	−0.156	0.197	−0.790	0.429	−0.542	0.230	
HH owns animals/poultry	−0.195	0.180	−1.080	0.278	−0.548	0.157	
Constant	0.928	0.737	1.260	0.208	−0.517	2.372	
Mean dependent var	0.833	SD dependent var				0.373	
Pseudo r-squared	0.111	Number of obs				348	
Chi-square	37.424	Prob > chi2				0.273	
Akaike crit. (AIC)	346.877	Bayesian crit. (BIC)				477.852	

*** $p < .01$, ** $p < .05$, * $p < .1$ are 1%; 5%, and 10% significance levels

its ability to effectively and proportionately handle both continuous and binary (dummy) variables and to predict distributions more accurately than other models, such as Ordinary Least Squares (OLS) and Logit models. One limitation of OLS is that it can produce predicted values outside the 0–1 range when used with binary dependent variables and may not accurately model non-linear relationships. Conversely, while the probit model assumes that the outcome variable is driven by an underlying continuous variable, the Logit model does not make this assumption, which affects its accuracy in predicting outcome variables and thus was avoided in this analysis.

The overall results of the probit analyses indicate that mode of farmland acquisition, access to credits, and the distance of the River Nile to plot in Kolye West were positively and significantly influencing the adoption of agroforestry by smallholder farmers (Table 7). The mode of farmland acquisition and ownership has long been observed as a critical determinant of agroforestry adoption by smallholder farmers. In South Sudan, particularly in Juba county, the acquisition of land in most rural areas is through inheritance and the traditional customary land system, and therefore, smallholder farmers live under the control of their family heads, subject to the rule of the traditional village chiefs. In this case, cultivation rights are also inherited rather than by ownership, and therefore, any tree planting program on farmland as a long-term investment strategy must be through consultation with the respective family heads or clan heads. The positive significance of the mode of farmland acquisition (inheritance) demonstrates that farmers with secured land rights are more likely to adopt AF practice at a 10% statistically significant level (Table 7). Our current findings are in agreement with the study results found by Obeng and Weber (2014) and Insaadoo et al. (2012).

The probit results further demonstrate that there is a significantly positive relationship between access to credit and farmers' adoption decisions. This indicates that every additional unit of credit or loan a smallholder farmer can obtain will ultimately raise the probability of adopting agroforestry by 72.6% (Table 7). This suggests that farmers are more inclined to invest in agroforestry land uses after receiving credit or loan support, which helps provide farm inputs such as seeds, seedlings, pesticides, and fertilizers. This may be because smallholder farmers

tend to expand and diversify their production and cropping systems as a way to guard against climate-induced shocks. These findings align with studies by Nicli et al. (2019) and Matata et al. (2010), who confirmed that access to microfinance, credit, or loans enables farmers to obtain necessary inputs for successful agroforestry adoption, making it positively related to their adoption decisions. The dummy variable for distance to the River Nile in Kolye West was found to positively influence agroforestry adoption at a 5% significance level. This indicates that farmers are more likely to adopt agroforestry when they have reliable water sources for their farms. Similar results were reported by Tanti and Jena (2023) and Mittal and Mehar (2016) in their study on socio-economic factors affecting the adoption of climate-smart practices and modern information and communication technology by farmers, respectively.

Factors influencing the adoption of different agroforestry practices by smallholder farmers

This section presents the estimated results of the multivariate probit regression model for the determinants of smallholder farmers' adoption decisions for different agroforestry practices. These practices were simultaneously observed as outcome variables and computed alongside several other controlling independent variables. While other factors are kept constant, these variables categorically and significantly explained the farmers' adoption decisions to practice a particular type of agroforestry. The results are presented in Table 8.

The MVP model results reveal that the Log Likelihood Ratio and a Chi-square test values of -767.178 and 295.19 , respectively, assessed the model's efficacy, with 10 degrees of freedom (DF). The Wald $\chi^2(165) = 511.36$ is highly significant at a 1% significance level ($p\text{-value} < 0.001$), confirming that at least one predictor significantly improves the model's fit. This indicates that the model is well-specified and fits our data reasonably well, and therefore allows us to reject the null hypothesis that all the regression coefficients included in the estimation are collectively equal to zero.

The results further show variations in farmers' selection patterns across the five different combinations of agroforestry practices. Therefore, there is a possibility that farmers' decisions to adopt specific

Table 8 Estimated parameters of smallholder farmers' attributes on adoption of different agroforestry practices using the Multivariate Probit Regression Model (N = 348)

Variables	SCL	HG	BP	WL	AC
Female-headed household	−0.174 (0.213)	−0.117 (0.229)	−0.140 (0.238)	−0.454** (0.228)	−0.166 (0.209)
Age	0.003 (0.007)	−0.008 (0.007)	−0.006 (0.007)	−0.002 (0.008)	−0.010 (0.007)
Marital status	0.063 (0.197)	−0.188 (0.186)	−0.113 (0.186)	0.167 (0.191)	−0.089 (0.180)
Native farmer	0.072 (0.224)	0.056 (0.210)	−0.057 (0.245)	0.089 (0.230)	0.280 (0.213)
Years of farming experience	0.011 (0.008)	0.003 (0.008)	0.006 (0.008)	−0.002 (0.008)	0.004 (0.008)
Educational status	0.070 (0.170)	0.209 (0.178)	0.250 (0.167)	0.222 (0.175)	0.080 (0.166)
HH size	−0.006 (0.029)	−0.014 (0.030)	−0.013 (0.034)	−0.054* (0.032)	−0.010 (0.026)
Farm size	0.020 (0.058)	−0.013 (0.068)	−0.064 (0.068)	−0.082 (0.063)	0.052 (0.058)
Distance to farm plot	0.026 (0.027)	0.023 (0.029)	−0.044 (0.035)	−0.007 (0.034)	−0.021 (0.031)
Mode of farmland acquisition	0.622** (0.290)	−0.635** (0.274)	−0.821** (0.307)	−0.361 (0.261)	−0.325 (0.289)
Size of the parcel/plot	−0.026 (0.063)	0.025 (0.070)	0.048 (0.071)	0.051 (0.065)	−0.106* (0.060)
Tenure1 (Owned family land)	−0.872** (0.407)	0.301 (0.385)	1.267*** (0.403)	0.092 (0.403)	−0.057 (0.423)
Tenure2 (Allocated family land)	−0.263 (0.363)	−0.512 (0.351)	−0.004 (0.364)	−0.076 (0.353)	−0.557 (0.402)
Tenure3 (Rented-in/Lease land)	−0.415 (0.374)	−0.023 (0.373)	0.672* (0.387)	−0.407 (0.401)	0.017 (0.420)
Tenure4 (Community land)	0.403 (0.376)	−1.284*** (0.410)	−0.195 (0.412)	−0.617 (0.414)	0.021 (0.393)
Tenure5 (Government allocated)	−0.411 (0.568)	0.396 (0.626)	−0.271 (0.868)	−0.886 (0.799)	0.359 (0.593)
Water1 (rain-fed)	0.173 (0.246)	0.027 (0.245)	−0.464** (0.221)	0.081 (0.228)	0.146 (0.212)
Water2 (flood water from river/swamps)	−0.571 (0.498)	1.286*** (0.454)	−0.087 (0.425)	0.533 (0.396)	1.176** (0.413)
Water3 (diversion from river water)	1.031** (0.430)	−0.592 (0.461)	−0.719 (0.450)	−0.266 (0.463)	−0.129 (0.429)
Soil2 (Loamy soil)	−0.016 (0.327)	0.037 (0.389)	−0.027 (0.343)	0.316 (0.332)	−0.129 (0.356)
Soil3 (Clay soil)	0.031 (0.337)	0.180 (0.384)	−0.156 (0.351)	0.595* (0.345)	0.300 (0.355)
Slope2 (Moderate slope (6–20%))	−0.142 (0.168)	0.325** (0.167)	0.344** (0.164)	−0.023 (0.178)	0.011 (0.158)
Slope3 (Steep slope (> 21%))	0.070 (0.314)	−0.107 (0.355)	−0.338 (0.361)	0.095 (0.352)	−0.616 (0.395)
Distance from the Nile to plot in Kolye East	−0.098 (0.168)	−0.323* (0.184)	−0.218 (0.169)	−0.171 (0.173)	−0.097 (0.166)
Distance from the Nile to plot in Kolye West	−0.742*** (0.301)	−0.432 (0.335)	0.080 (0.287)	−1.026*** (0.319)	−0.272 (0.270)

Table 8 (continued)

Variables	SCL	HG	BP	WL	AC
Distance from the Nile to plot in Gumbo	0.184 (0.604)	0.376 (0.663)	−0.272 (0.641)	−0.988* (0.600)	0.059 (0.575)
Distance from the Nile to plot in Tokiman	0.740 (1.014)	−1.924* (1.150)	−1.873* (1.085)	−3.984** (1.476)	0.111 (0.910)
HH access to credit	−0.196 (0.253)	−0.047 (0.244)	−0.525** (0.252)	−0.814*** (0.253)	−0.159 (0.245)
HH access to improved seeds	0.328** (0.163)	−0.353** (0.181)	−0.047 (0.170)	−0.503** (0.184)	−0.220 (0.163)
Distance to Markets	0.003 (0.028)	0.058** (0.028)	−0.011 (0.028)	0.022 (0.032)	0.040 (0.027)
Off-farm income sources	−0.019 (0.166)	0.186 (0.171)	0.206 (0.163)	−0.084 (0.173)	0.254 (0.163)
Extension/Agent contact	−0.067 (0.169)	−0.263 (0.187)	0.457*** (0.174)	0.304 (0.189)	0.265 (0.174)
HH owns animals/poultry	0.238 (0.165)	−0.334** (0.160)	0.108 (0.159)	0.283* (0.163)	0.243 (0.156)
Constant	−0.354 (0.582)	0.314 (0.651)	0.078 (0.608)	−0.089 (0.613)	−0.496 (0.640)

(a) Figures in parentheses are robust standard errors

(b) *, **, and *** represents statistical significant at 10%, 5%, and 1% respectively;

(c) Likelihood ratio test of $\rho_{21} = \rho_{31} = \rho_{41} = \rho_{51} = \rho_{32} = \rho_{42} = \rho_{52} = \rho_{43} = \rho_{53} = \rho_{54} = 0$: $\chi^2(10) = 295.19$; Wald $\chi^2(165) = 511.36$; Log pseudolikelihood = -767.178 ; Prob > $\chi^2 = 0.0000$

(d) The pairwise numbers in Rho in (c) above refer to different types of agroforestry practices: 1 = Scattered trees on cropland (SCL), 2 = homegardens (HG), 3 = boundary planting (BP), 4 = woodlots (WL), and 5 = alley cropping (AC)

(e) Number of observations: 348

practices are linked to their choices of other practices. To examine this, pairwise correlation coefficients across the residuals of the MVP model are computed (Appendix Table 13). The MVP results showed that, after accounting for the influence of observed factors, the coefficients indicated the correlation between five different practices. Moreover, most of the pairwise correlation coefficients of the residuals for agroforestry practices are significant (Appendix Table 13), supporting our hypothesis that the error terms in the decision-making equation are correlated, and justifying the use of the MVP model over an independent probit model. It is important to note that a positive sign indicates complementarity between the practices, meaning higher values increase the likelihood of adopting agroforestry practices, whereas a negative sign suggests substitutability, meaning higher values tend to decrease the probability of adoption. The pair-wise correlation coefficient results show that homegarden is positively correlated with boundary planting, woodlot, and alley cropping, indicating

these practices are often adopted together. The practice of scattered trees on cropland is positively correlated with woodlot and alley cropping, but negatively correlated with homegardens and boundary planting, implying they can serve as substitutes (Appendix Table 13). Categorically, the results identify key factors that significantly influence farmers' decisions to adopt, or not adopt, individual or combined agroforestry practices. These include:

Gender

The results show that the gender of household heads (female) was found to negatively and significantly affect the adoption decision of farmers for WL practice, which suggests that the adoption of WL practices reduces with more female-headed households. In other words, households with more females as heads are less likely to adopt WL agroforestry practice by about 45% probability at a 10% significance level. When other determining factors are kept constant

(*ceteris paribus*), this finding further suggests that male household heads are more likely to practice such agroforestry by about 55% per unit increase of adoption than their female counterparts (Table 8). Similar findings are observed in a recent study conducted by Neway and Zegeye (2022).

Household access to credit

Access to credit was found to have a negative and significant relationship with smallholder farmers' decision to adopt WL and BP agroforestry practices. Its impact was strong for WL and moderate for BP at a 1% and 5% significance level, respectively. This indicates that each unit of credit or loan a smallholder farmer can access will ultimately reduce the odds of adopting WL and BP by 0.814 and 0.525, or over 80% and 50%, respectively (Table 8). This suggests that farmers lacking access to credit are less likely to invest in such practices despite having collateral security. This may be because farmers have no additional capital to invest and cannot generate more income to support adopting these agroforestry practices. The anticipation of immediate harvest benefits to meet household needs also discourages many farmers from investing their hard-earned credits or loans. Instead, many divert credits to meet short- and medium-term investments or projects. Another reason could be that intensive management practices such as pruning, pollarding, weeding, thinning, and other silvicultural operations, which often require high costs and hard labor, may demotivate farmers from using credits effectively for adopting WL and BP agroforestry practices. Our findings contrast with studies by Nicli et al. (2019) and Matata et al. (2010), which indicated that access to microfinance, credits, or loans enables farmers to obtain agroforestry inputs for successful adoption, and thus, should positively influence farmers' decision to adopt. Additionally, in many rural areas of South Sudan, like Juba, microfinance and credit institutions are limited or nonexistent; therefore, farmers' willingness to invest in practices like WL agroforestry may be limited by their lack of access to formal credit providers who could offer them credit despite collateral and security. Similar observations were highlighted in a study by Kiplimo et al. (2015).

Household access to improved seeds and seedlings

Access to improved seeds and seedlings was found to be positively and significantly associated with SCL agroforestry adoption at a 5% significance level ($p < 0.05$). The analysis revealed that a one-time increase in the use of improved seeds could substantially raise the odds of SCL adoption by 0.328, or over 30% (Table 8). Household respondents emphasized the need for free, quality, and improved seeds and seedlings of various agroforestry species. Therefore, government support, such as seed subsidies and credit, is likely to boost farmers' adaptive capacity to consistently adopt SCL because it requires fewer inputs (seeds, seedlings, pesticides, etc.) dispersed on the cropland. This support should be provided to individual farmers or farmer groups to encourage innovation in agroforestry technologies. This finding aligns with the results of a study by Alemayehu and Simeneh (2024), which also found that access to improved seeds and tree seedlings influences household adoption of agroforestry practices. Conversely, the results showed a significantly negative relationship between improved seeds and farmers' decisions to adopt HG and WL practices, implying that farmers are less likely to adopt these by odds of 0.353 and 0.503, respectively. This may be due to factors such as the high labor demands, small household and farm sizes, unpredictable land tenure systems, and the high costs of inputs.

Household distance to markets

Distance to the market variable is an important factor influencing the adoption of different agroforestry practices. The results show that households' distance to market positively and significantly affects the adoption of HG agroforestry practices at a 5% significance level (Table 8). This indicates that when villages are located near town centers and markets, farmers are more likely to adopt HG practices because access to inputs and the sale of agroforestry products becomes easier. Additionally, HGs are situated within homesteads, allowing farmers to adopt the technology easily, secure products adequately, and achieve high yields. Surplus products can then meet market demands, increasing household incomes. Furthermore, even farmers located farther from input and output markets may form farmers' groups to benefit

from economies of scale, especially when purchasing inputs or selling outputs. This can make adopting HG agroforestry practices simpler. These findings align with those of Mittal and Mehar (2016) and Trebbin (2014), both of whom noted that when smaller farmers are far from input and output markets, they are more likely to join farmers' groups to take advantage of economies of scale, particularly when procuring inputs or selling their agroforestry products.

Extension agent contact/visits

Extension contact plays a crucial role in the diffusion of skills and knowledge, including the sharing and exchange of technical information among and between smallholder farmers and extension workers, positively influencing adoption decisions. The results of the frequency of extension contact or visits were found to be highly positive and significantly influencing household farmers' adoption decisions on BP at a 1% significance level. This implies that a unit increase in extension contact by farmers will likely increase the probability of their adoption of BP practice by odds of 0.457 (Table 8). Another reason is that household farmers with close contact with extension agents are more likely to adopt BP practice than those who reside far away and with a low frequency of extension visits. Our study findings are consistent with those studies conducted by Alemayehu and Simeneh. (2024) and Berhanu and Atnaфу. (2023), who both reiterated that access to extension agents has a positive influence on the adoption of agroforestry practices such as BP. However, according to the KIIs and FGDs held, there persists a heterogeneity in the farmers' information dissemination and extension service provision, as most farmers were unaware of the presence of extension facilities, which kept them away from accessing extension services. They (farmers) also reported that only a few influential community members and farmers received continuous support, with the poor and marginalized farmers always neglected for extension support, posing barriers to adoption. Therefore, the significance of extension contact suggests that contact with research and extension is crucial for the successful adoption of those particular agroforestry practices (Tanti and Jena 2023; Nkamleu and Manyong 2005).

Household size

Our study results found that household size has a negative and significant association with the adoption decision of farmers for WL practice. This implies that a family with few members, also impacted by a high dependency ratio, could experience a low labor supply for WL agroforestry. This is because WL practices require intensive labor for land clearance, planting, and other silvicultural operations, including time. The results indicate that a unit decrease in household size will subsequently decrease adoption rates by 5.4% (Table 8). The results further show that households with low labor availability in adult equivalents are less likely to adopt WL agroforestry practices. This finding agrees with the study results obtained by Berhanu and Atnaфу (2023), Syano et al. (2022), and Obeng and Weber (2014). This study also corroborates with those of Uisso and Masao (2016), who found no statistically significant association between household size and adoption of agroforestry practices.

Livestock ownership

The results indicate that the variable of livestock ownership has a positive and significant association with farmers' decisions to adopt WL practices at a 10% significance level (Table 8). This means that a farmer who produces animals or poultry can use them as a source of financial assets during a financial emergency, thus increasing the likelihood of WL adoption. This allows them to sell their animals and invest in addressing the household shocks, such as climate-related shocks and food insecurity, by adopting long-term agroforestry practices such as WL for future remedy. Farmers could also sell their livestock to generate income and diversify their farming systems and production basket through WL agroforestry practices (Tanti and Jena 2023). On the other hand, WL provides livestock farmers with fodder in the form of cut and curry because they may integrate multipurpose agroforestry tree species. Livestock ownership has a negative and significant impact on the practice of BP, indicating that farmers who do not own animals are less likely to adopt BP practice by odds of 0.334 at a 5% significance level. It also suggests that farmers may feed animals on species of BP, thereby reducing their quality.

Parcel size

Parcel or plot size also influences the adoption decision of farmers as well as their capacity to access credits. The results show that parcel size has a negative and significant influence on the farmers' adoption decision for AC agroforestry practice at a 10% significance level (Table 8). This suggests that small farmers with small parcel sizes are less likely to adopt the practice of AC because it requires enough space to make rows(alleys). They are also less likely to diversify their production and agroforestry cropping patterns. From the descriptive statistics, it can be noted that most farmers were smallholders with small farm plots of approximately 2 ha per household. This indicates that a decrease in each unit of parcel will ultimately reduce the odds of adopting AC by 0.106. Moreover, plot size also determines the amount of credit a farmer can access or borrow from microfinance and credit institutions. Notwithstanding other factors being kept constant, farmers with smaller plots are less likely to receive more credits from financial institutions, and the reverse is true with farmers having larger plot sizes.

Mode of farmland acquisition

Farmland acquisition and ownership have long been observed as a critical determinant of smallholder farmers' agroforestry adoption decisions. The results of its coefficient were found to negatively and significantly influence adoption decisions for HG and BP, while having a positive and significant impact on SCL practice. The statistically negative significance of the mode of farmland acquisition (inheritance) demonstrates that farmers with inherited lands are less likely to adopt HG and BP AF practices at a 5% significance level (Table 8). This could be due to disagreement among heirs subject to shares of their parental lands. Our current findings are in agreement with the study results found by Obeng and Weber (2014) and Insaiddoo et al. (2012). The positive coefficient of the mode of farmland acquisition at a 5% statistically significant level on SCL suggests that with other factors kept constant, farmers are more inclined to consider adopting the practice and could substantially raise the odds of SCL adoption by a factor of 0.622 (Table 8). The reason may be that land inheriting farmers could scatteredly plant or retain only

important multipurpose tree species with cultural, socioeconomic, and ecological values on their farms, which do not interfere with the growth of other agroforestry components.

Other factors influencing farmers' adoption of agroforestry practices

Our MVP model includes several other factors to identify their influence, as they are found to have a significant influence on the agroforestry adoption decision of farmers. The results show that the dummies for the distance from the River Nile to plots in Kolye East, Kolye West, Gumbo, and Tokiman Island all affect the adoption decision of farmers for SCL, HG, BP, and WL practices negatively and significantly, implying that farmers also find difficulty in installing irrigation equipment within a greater radius to feed agroforestry farms. This suggests that if other factors remain constant (*ceteris paribus*), farmers living within the radius of these villages to access the Nile water for agroforestry species are less likely to adopt SCL, HG, BP, and WL practices. This inference further states that farmers may be motivated to adopt such practices, but only as a complement to conventional agriculture or forestry. This finding agrees with the study conducted by Mittal and Mehar (2016).

One critical aspect that determines a farmer's decision to adopt agroforestry is the farm slope. The results show a positive and significant association between slope2 (moderate slope) and farmers' adoption decision for HG and BP, meaning that most farmers prefer to establish those agroforestry practices in a landscape with a moderate slope gradient, and thus are more likely to adopt them. While clay soils have a positive and significant impact on the adoption of WL practice, the tenure systems varied among those practices, with tenure 1 and tenure 3 positively and significantly influencing farmers' adoption decision for BP practice, increasing the odds by a factor of 1.267 and 0.672, respectively (Table 8). This suggests that farmers with land tenure 1 and 3 are more likely to adopt HG practices compared to other tenure systems. While land tenure 1 and 4 negatively and significantly influence the adoption decision of farmers for SCL and HG, at 5% and 1% significance level, respectively. This means that farmers with such land tenure systems (1 and 4) are less likely to adopt those practices. Water sources 2 and 3 were

found to positively and significantly influence adoption decisions of farmers for HG, AC (water source 2), and SCL (water source 3). Farmers can conserve water in reservoirs for long-term use during the planting season. This can be accessed from surface run-off as floods, and through the diversion of rivers/streams into farmlands. The positive significance value indicates that access to different water sources for agroforestry species is more likely to influence farmers to adopt the practices. However, a high reliance on rainfed water sources (water source 1) negatively and significantly influences farmers' adoption decisions for BP. This could be attributed to the unpredictable nature and variability in the intensity of rainfall during the planting seasons. Therefore, with the negative odds of rainfed water source, there is a probability that farmers are less likely to adopt the practice of BP agroforestry.

Main constraints to agroforestry adoption and opportunities for promoting the adoption of agroforestry

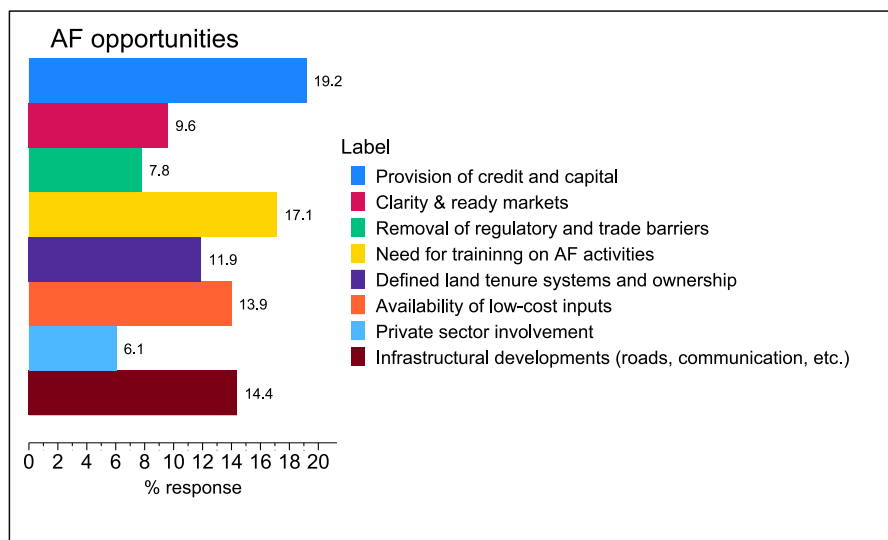
Many factors constrain the adoption of agroforestry and allow household farmers to decide whether to adopt or not to adopt agroforestry practices. The results of the constraints/barriers indicate that a lack of low-cost and quality inputs (1st rank), high rates of insecurity (2nd rank), lack of capital (3rd rank), insufficient labor (4th rank), and land disputes (5th rank) were major constraints to agroforestry adoption

among all the survey sites (Table 9). High rates of insecurity instill fear and prevent households from moving to farms and participating in agriculture and agroforestry practices. The unavailability of good planters and species of woody perennials makes it difficult to establish a tree-based component setup of agroforestry (Gupta et al. 2023; Saravanan and Berry 2021; Ibrahim et al. 2019). Our current study concurs with the findings of Pathania et al. (2020), where a higher number (about 80%) of farmers reported a lack of good and quality planting materials to influence the adoption of agroforestry in the study area. Apart from insecurity constraining adoption decisions of household farmers, the lack of capital to invest in agroforestry was considered a third major constraint to the uptake of agroforestry practices by smallholder household farmers in Rajaf Payam. This has subsequently affected their purchasing power of good and quality tree planting inputs (improved seeds, seedlings, and equipment), suggesting a need for external support and extension services from agroforestry stakeholders (NGOs, government institutions, UN Agencies, CBOs, etc.). As supportively put, evidence from the previous study by Alemayehu and Bewket (2017) showed that limited capital to purchase quality agroforestry inputs by smallholder farmers is a major constraint to effective agroforestry adoption decisions and adaptation to climate change. However, the results of the KIIs and FGDs mentioned the provision of credit and capital, education and awareness of farmers, infrastructural development, and provision

Table 9 The main constraints to the Adoption of Agroforestry practices in Rajaf Payam

The main constraints to AF adoption	Frequency (F)	Percentage (%)	% Ranking
Lack of low-cost and quality inputs	75	21.55	1st
Insecurity issues	62	17.82	2nd
Lack of capital to start	57	16.38	3rd
Insufficient labor	38	10.92	4th
Land disputes	26	7.47	5th
Destruction from cattle (astray)	22	6.32	6th
Lack of knowledge	17	4.89	7th
Pests and diseases	15	4.31	8th
Uncontrolled bush & forest fires	13	3.74	9th
Climate change problems	11	3.16	10th
Long maturity period	8	2.30	11th
Infertile soils	4	1.15	12th
Total	348	100	

Fig. 4 Opportunities for successful adoption of agroforestry practices in Rajaf study sites



of low-cost inputs as major opportunities that can motivate and encourage household farmers to adopt agroforestry practices (Fig. 4).

Conclusion

This study explored the factors influencing the adoption of agroforestry practices among smallholder farmers in Rajaf communities. The significance of these variables is the necessary preconditioning factors that enable smallholder household farmers to overcome the major constraints limiting their adoption decisions to practice agroforestry. The findings reveal that five agroforestry practices were identified, and their adoption rates varied across the study area. The most commonly adopted practices included scattered trees on cropland, home gardening, and boundary planting. The multivariate probit results indicate that gender, household size, credit access, access to improved seeds, extension contact, distance to markets, livestock ownership, mode of farmland acquisition, parcel size, distance to River Nile, land tenure system, and slope had statistically significant associations with the adoption decision of farmers. They are considered important factors influencing the adoption of agroforestry as a single practice or a combination of practices. These results can be used further to design programmes specific to farmers' profiles and allow for related agroforestry stakeholders to better anticipate which type of farmers would use

different agroforestry practices in combination with other practices, because their adoption often shows complementarity. Additionally, our study found that farmers' preferred agroforestry species were mainly fruit trees, including *Mangifera indica*, *Citrus sinensis*, *Carica papaya*, and *Azadirachta indica*, suggesting further mapping of key agroforestry species in the study area in future research to ascertain their economic and environmental values to the populace. Our study further showed that farmers' adoption decisions were influenced by benefits obtained from agroforestry tree and shrub species, notably for food, shade, protection, construction, livestock fodder, and fuelwood. This paper further investigated constraints that limit farmers' adoption decisions of agroforestry practices in the study area. The results show a lack of low-cost and quality inputs, insecurity, a lack of capital to kick-start, insufficient labor, land disputes, and destruction of farm crops by astray livestock were the common constraints to farmers' adoption decisions. However, farmers reported that for successful adoption of agroforestry practices and to increase adoption rates, opportunities such as access to credit, farmers' training, and development of roads and communication infrastructure, as well as ready markets for agroforestry inputs and output, are the key drivers. Therefore, to out-scale agroforestry adoption, proper land use management, policy support and regulations, provision of free or subsidized extension services, sharing of field-related experience and demonstrations, as well as sharing success stories, should be

implemented. Moreover, much effort should focus on awareness and education of household farmers to increase their understanding of the importance of agroforestry technologies to their livelihoods.

Policy implications and recommendations, and future areas of research

From the study findings, several policy implications and recommendations can be drawn as follows: Agroforestry adoption is key to accountability to households' food security and its climate change adaptations and mitigation roles. Therefore, the development of appropriate interventions to promote agroforestry practices ensures subsequent adoption by farmers, lessens rural poverty, improves food and nutritional security in households, and delivers ecosystem services that ameliorate micro-climatic changes through biodiversity and natural resources conservation and management. Formulating and advocating for effective policy frameworks provides farmers with a key for scaling up and promoting the adoption of new and improved agroforestry practices and technologies. The study findings, therefore, can inform policy and decision-makers, agroforestry stakeholders, and other development partners to promote the adoption of agroforestry practices, thus accelerating sustainable and holistic uptake of conjoint agriculture and forestry management activities within the study region. This underscores the importance of government support and private sector involvement in developing and implementing policies that allow farmers to recognize the multifunctional benefits accrued from practicing agroforestry. Education and awareness of farmers, including extension service assistance in providing quality training, low-cost, and quality planting materials such as improved seeds and seedlings, can encourage and motivate household agroforestry farmers, increasing adoption rates. Furthermore, to enable household farmers to benefit and enjoy economies of large-scale production and help them easily access credit and market facilities, research extensions, land tenure rights and security, formal grouping of farmers into associations should be encouraged. Additionally, to ensure robust agroforestry sustainability and overcome adoption limitations, government and other policymakers (NGOs

and development partners) are key agroforestry stakeholders who can facilitate an enabling environment by providing farmers with motivational incentives, thus encouraging the adoption and scaling-up of agroforestry practices. Generally, it is worth noting that peace is paramount if this should happen for any successful implementation of agroforestry interventions, especially in the case of Rajaf study area in South Sudan.

Research limitations

One of the limitations of our study lies in the small sample size selected, which is attributed to the limited resources, such as time and funds needed to increase the number of respondents. The study also encountered a higher number of agroforestry adopters than non-adopters. This perhaps could explain why most of the independent variables had statistically insignificant influence on the dependent variable (binary dummy for agroforestry adoption) and outcome variables (agroforestry practices). Secondly, the study is limited to only five agroforestry practices and focuses on a few household characteristics. In this regard, there is a possibility of overlooking the potential of other agroforestry practices and determinants that would significantly influence farmers' adoption decisions, impacting their rural livelihoods. Thirdly, our study utilized data generated at the household survey level because plot-level data were not available. Plot-level data can better capture the heterogeneous factors related to socioeconomic, institutional, and biophysical aspects at a fine scale, which is essential for understanding the nuanced effects of the adoption of agroforestry practices. The lack of such plot-level data may mean that the study analysis overlooks important sources of variation that could more effectively explain smallholder farmers' adoption behaviors and the influence of associated adoption factors. Therefore, the study recommends that future research should focus on collecting data at the plot level and from a larger, more representative sample. Still, further studies in the region are necessary to identify additional agroforestry practices and shared factors that could influence farmers' decisions to adopt these practices.

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Author contribution This manuscript is a part of a PhD dissertation of the main author. Contributors are JMM: conceptualisation and methodology, instrument preparation, field data collection and investigation, formal analysis, and writing of the original draft. TS: Conceptualisation and directives, supervision, review, proofreading, editing, and comments on the manuscript. All authors.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical Statement The data for this study were collected in compliance with relevant institutional laws and guidelines approved by the local administration of the study area. The privacy and confidentiality rights of participants were also fully observed and respected.

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Appendices

See Tables 10, 11, 12 and 13.

Table 10 Preliminary highlights of reconnaissance survey and questionnaires pretesting

Village	No. of HH respondents	HH access roads	Language used	AF practices surveyed	Common tree species	Community perception (Use of AF Species)
Kolye East	5	Multiple/ Open /accessible by car/foot	Bari, Arabic, English	WL, HG, SCL, AC, BP	<i>Mangifera indica</i> , <i>Carica papaya</i> , <i>Azadirachta indica</i> , <i>Ficus benjamina</i> , <i>Buxus sinica</i> , <i>Psidium guajava</i> , <i>Citrus sinensis</i> , <i>Senna siamea</i> , <i>Borassus aethiopum</i> , <i>Tectona grandis</i> , <i>Kigelia africana</i> , <i>Acacia sebertiana</i> , <i>Gmelina arborea</i> , <i>Annona squamosa</i>	Fo, Fd, Fw, Med, Sh, Ti, Co, Cul, SF
Kolye West	4	Open/ Accessible by car/foot	Bari, Arabic	SCL, HG, HC, AC		Fo, Co, Sh, LF, Med, Ti, CC, Fw, Fd
Gumbo	4	Multiple/ Open/ Accessible by car/foot	Bari, Arabic, English	WL, HG, AC, BP, GL		Fo, Fw, Sh, Jc, Med, CC, Aes/Orn
Tokiman Island	3	Single/only accessed by boat	Bari, Arabic,	AC, HG, SCL		Fo, Med, Jc, Sh, Fd, Fw, SF, Cul, SF

Agroforestry land use/practices include: *HG* Homegardens, *SC* Scattered trees on cropland, *HC* trees on compound, *GL* trees on grazing land, *WL* Woodlot plantation, *BP* Boundary planting, *AC* Alley cropping, *LF* Live fences; Common uses of tree species surveyed in the study areas include: *Fo* Food, *Fw* Fuelwood, *Sh* Shade, *Jc* Making Juice, *Ti* Timber, *Med* Medicine, *SF* Soil fertility, *Fd* Animal Fodder, *Co* Construction material, *Aes/Orn* Aesthetic/ornamental use, *Cul* Cultural value/use

Table 11 The botanical and common English names of the top dominant woody perennial species preferred within the agroforestry study sites

Species No	Species Name	Botanical Family Name	Common/ English Name	Fr	%
1	<i>Mangifera indica</i>	Anacardiaceae	Mango	141	26.91
2	<i>Citrus sinensis</i>	Rutaceae	Orange	83	15.84
3	<i>Carica papaya</i>	Caricaceae	Papaya	53	10.11
4	<i>Azadirachta indica</i>	Meliaceae	Neem Tree	48	9.16
5	<i>Tectona grandis</i>	Verbenaceae	Teak	38	7.25
6	<i>Psidium guajava</i>	Myrtaceae	Guava	27	5.15
7	<i>Gmelina arborea</i>	Lamiaceae	Beechwood	24	4.58
8	<i>Ficus benjamina</i>	Moraceae	Weeping Fig	18	3.44
9	<i>Trichilia hirta</i>	Meliaceae	Hairy Mahogany	17	3.24
10	<i>Annona squamosa</i>	Annonaceae	Sugar Apple	17	3.24
11	<i>Senna siamea</i>	Fabaceae	Siamese Cassia	16	3.05
12	<i>Pithecellobium dulce</i>	Fabaceae	Monkeypod	14	2.67
13	<i>Tephrosia vogelii</i>	Fabaceae	Fish Bean	9	1.72
14	<i>Buxus sinica</i>	Buxaceae	Chinese Boxwood	8	1.53

Table 12 Agroforestry practices and common uses of the top woody perennial species identified in Rajaf Payam

Tree species name	Species common AF practices niche	Species uses perceived by respondents
<i>Mangifera indica</i>	HG, SCL, WL	Fo, Fw, Sh, Jc, Med, CC
<i>Citrus sinensis</i>	WL, HG, SCL, AC, BP	Fo, Med, SF, Fd, Jc
<i>Carica papaya</i>	HG, SCL, WL, AC	Fo, SF, Med, Jc, Fd
<i>Azadirachta indica</i>	HG, SCL, BP, AC	Fo, Fd, Fw, Med, Sh, Ti, Co
<i>Tectona grandis</i>	WL, SCL, BP	Co, Fw, Ti, Med
<i>Psidium guajava</i>	HG, SCL, WL, AC, BP	Fo, Fd, Sh, Jc, SF
<i>Gmelina arborea</i>	WL, BP, SCL, LF	Co, Ti, Fd, Fw, LF, Cul
<i>Ficus benjamina</i>	HG, SCL, WL, HC, BP	Co, Sh, Ti, Fw, Med, Fd, Aes/orn, CC
<i>Trichilia hirta</i>	WL, SCL, BP	Fo, Fd, Med, Poi, LF
<i>Annona squamosa</i>	HG, SCL, AC	Fo, Fd, Med, Jc, SF
<i>Senna siamea</i>	WL, BP, SCL, HG, LF	Co, Sh, LF, Med, Ti, CC, Fw, Fd
<i>Pithecellobium dulce</i>	GL, WL, HG, SCL	Fo, Fd, Fw, Med, Sh,
<i>Tephrosia vogelii</i>	AC, SCL, HG, BP, WL	SF, Fd, Sh, Med, Poi, CC, LF
<i>Buxus sinica</i>	SCL, AC, HG, WL, GL	Aes/orn, Cul, Med, Perf

Agroforestry land use/practices include: *HG* Homegardens, *SCL* Scattered trees on cropland, *HC* trees on compound, *GL* trees on grazing land, *WL* Woodlot plantation, *BP* Boundary planting, *AC* Alley cropping, *LF* Live fences; Common uses of tree species surveyed in the study areas include: *Fo* Food, *Fw* Fuelwood, *Sh* Shade, *Jc* Making Juice, *Ti* Timber, *Med* Medicine, *SF* Soil fertility, **Fd** = Animal Fodder, *Co* Construction material, *Aes/Orn* Aesthetic/ornamental use, *Poi* use as poison & insecticide, *Perf* Making perfume, *Cul* Cultural value/use

Table 13 The correlation coefficients of the error term between pairwise adoption practices obtained in the MVP model estimation

Binary correlation	Correlation coefficient ^a	Standard error
rho21	− 0.011	0.084
rho31	− 0.033	0.090
rho41	0.181*	0.086
rho51	0.249**	0.080
rho32	0.537***	0.077
rho42	0.649***	0.082
rho52	0.699***	0.063
rho43	0.698***	0.069
rho53	0.747***	0.060
rho54	0.848***	0.037

(a) Likelihood ratio test of $\rho_{21} = \rho_{31} = \rho_{41} = \rho_{51} = \rho_{32} = \rho_{42} = \rho_{52} = \rho_{43} = \rho_{53} = \rho_{54} = 0$: $\chi^2(10) = 295.19$; Wald $\chi^2(165) = 511.36$; Log pseudolikelihood = −767.178; Prob > $\chi^2 = 0.0000$

(b) The pairwise numbers in Rho refer to agroforestry practices: 1 = Scattered trees on cropland, 2 = homegardens, 3 = boundary planting, 4 = woodlots, and 5 = alley cropping

(c)^a Correlation coefficient between the residuals from the multivariate probit equations

(d)*, **, and *** indicates statistical significance at 10%, 5% and 1% respectively

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