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Adoption determinants of improved cassava varieties and intercropping among East and Central African smallholder farmers

Paul Mwebaze¹ | Sarina Macfadyen² | Paul De Barro³ |
Anton Bua⁴ | Andrew Kalyebi⁴ | Irene Bayiyana⁴ | Fred Tairo⁵ |
John Colvin⁶

¹Department of Environmental Science & Policy, the University of California Davis, Davis, California, USA

²Commonwealth Scientific and Industrial Research Organisation, Canberra, Australian Capital Territory, Australia

³Commonwealth Scientific and Industrial Research Organisation, Brisbane, Queensland, Australia

⁴National Crops Resources Research Institute, Kampala, Uganda

⁵Mikocheni Agricultural Research Institute, Dar es Salaam, Tanzania

⁶Natural Resources Institute, University of Greenwich, Kent, UK

Correspondence

Paul Mwebaze, Department of Environmental Science & Policy, the University of California, Davis, Davis, CA 95616, USA.

Email: pmwebaze@ucdavis.edu and mpaul48@hotmail.com

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Abstract

A key constraint to cassava productivity in Africa is the lack of adoption of improved cassava varieties tolerant to pests and diseases. To understand the drivers of adoption behavior, we examine the simultaneous adoption of improved cassava varieties and intercropping by 1200 smallholder farmers in Malawi, Tanzania, and Uganda. Using a linear model, we find that varietal characteristics, such as yield and early maturity, are critical drivers of adoption. Access to extension and credit is associated with an increase in the attractiveness of yield-improving characteristics. We conclude that a more targeted extension approach would increase technology adoption in these countries.

KEYWORDS

Food security, Improved cassava varieties, Intercropping, Smallholder farmers

JEL CLASSIFICATION

Q1 (agriculture), Q5 (environment and ecology), O3 (innovation, technological change)

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1 | INTRODUCTION

Cassava is the second most important food crop in Africa after maize and provides more than half of the dietary calories for over 200 million people in East and Central Africa (ECA) (Alene, 2013; FAO & IFAD, 2005; Reincke et al., 2018). It is produced by smallholder farmers whose average cultivated area is less than one hectare and often in households with female heads for home consumption (Masamha et al., 2018).¹ It is mainly grown under intercropping systems with other crops such as maize, legumes, and bananas. Africa is the world's largest cassava-producing region, accounting for nearly 61% of the global cassava output (FAO, 2023).² Moreover, cassava roots are significantly cheaper than grains such as maize and rice. It is also relatively tolerant of poor soils and seasonal droughts, making it a suitable food security crop, especially during conflicts (Bennett, 2015; Parmar et al., 2017). While other crops are projected to face significant adaptation challenges in Africa, cassava is resilient to climate change because of its drought tolerance, resilience on marginal agricultural lands, and ability to be left in the ground without harvesting for extended periods (Jarvis et al., 2012). Previous studies have emphasized the economic importance of cassava to smallholder farmers (Fermont et al., 2010; Johnson et al., 2006; Roothaert & Magado, 2011).

Cassava yields in Africa are the lowest in the world, with an average yield of 10 tonnes per hectare (tonnes/ha) compared to 26 tonnes/ha in India (FAO, 2023). Figure 1 shows changes in cassava yields over time in Malawi, Tanzania, and Uganda. In Tanzania and Uganda, there was a steady decline from 1990 onwards. The potential factors explaining the trends include pests and diseases, climate change, low-yielding varieties, declining soil fertility, and poor agronomic practices (Alene, 2013; Legg et al., 2006; Roothaert & Magado, 2011). By contrast, Malawian yields increased roughly ten times from the low point in the 80s due to the release of improved crop varieties (IVCs) (Alene, 2013). Fermont et al. (2009) estimated that cassava yields in East Africa could reach 20 Mt/ha using existing technologies and best practices. Yield potential in a well-controlled research setting with irrigation and fertilization was approximately 45 Mt/Ha (Tian et al., 2009). If translated to the farmer level, it would increase cassava production and improve food security and incomes among cassava farmers. Dethier and Effenberger (2012) have suggested that the two main explanations for low yields in Africa are a lack of appropriate technology and slow adoption. However, Suri and Udry (2022) point to several other constraints, such as credit and liquidity, insurance, information, high transaction costs, and imperfect labor and land markets.

There is extensive literature on technology adoption and the relationship between technology adoption and socioeconomic and policy variables in developing countries (e.g., Feder et al., 1985; Suri & Udry, 2022). Studies show that the wide adoption of new agricultural technologies effectively increases agricultural productivity (Minten & Barrett, 2008). Adoption is a process of willingly accepting innovation by the members of a social system (Rogers, 1962). Previous studies have investigated factors influencing technology adoption decisions and the intensity of adoption. Farm and farmer socioeconomic characteristics affected adoption in many of these studies. Farm size (Kassie et al., 2013), varietal attributes, especially taste, color, and drought tolerance (Kalema et al., 2022; Mafuru et al., 2008; Miriti et al., 2022), education (Kassie et al., 2013; Teklewold et al., 2013), extension (Ruzzante et al., 2021; Wossen et al., 2017), household size, accessible inputs and age of household head (Kondo et al., 2020; Simtowe et al., 2016) influenced the adoption of technologies. Beyond these factors cited above, Michler et al. (2019) found that profitability is more relevant than increases in yields in explaining technology adoption decisions.

¹However, the perception of cassava production as a “subsistence crop belonging to women” is changing, as a large share of the output is intended for commercialization, and the labor requirements are partially met by male members of the households (Fermont et al., 2010; Parmar et al., 2017).

²Cassava is a major crop in Nigeria, Mozambique, Zambia, DR Congo, Ghana, Malawi, Uganda, and Tanzania.

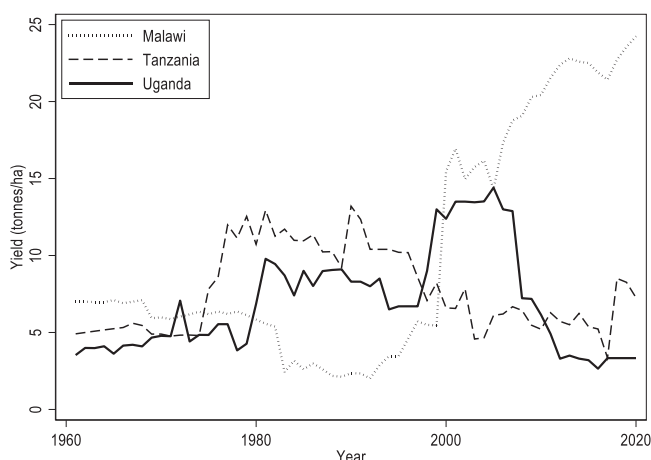


FIGURE 1 Cassava yields over time in Malawi, Tanzania, and Uganda Source: FAO (2023).

One of the critical constraints to cassava productivity in ECA is the lack of adoption of improved cassava varieties (ICV) bred to be resistant or tolerant to pests and diseases (Alene, 2013; Mbanjo et al., 2021). Many farmers still plant local varieties with low yields and high susceptibility to certain pests and diseases (Houngue et al., 2018). In particular, two diseases, cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), have negatively affected cassava production in Uganda, Tanzania, and Malawi (Chikoti et al., 2019; Macfadyen et al., 2018; Patil et al., 2015; Tomlinson et al., 2018; Vurro et al., 2010). At least three cryptic species vector the viruses that cause these diseases in the whitefly *Bemisia tabaci* complex known as the sub-Saharan African sub-group (Elfekih et al., 2021; Mugerwa et al., 2018). The disease can also be spread by moving infected cassava cuttings (Boykin et al., 2018; Macfadyen et al., 2018). This paper uses the common name “cassava whitefly” to refer to multiple species in the *B. tabaci* complex, including cassava within their host-plant range. Outbreaks of cassava whitefly and associated viruses have caused significant crop losses in ECA countries, resulting in hunger, food insecurity, and annual crop losses of approximately \$1.25 billion (Legg et al., 2006; Macfadyen et al., 2021). For example, in 2010, CBSD was listed among the seven most harmful plant diseases globally because of its negative impact on food security in Africa (Pennisi, 2010). Furthermore, cassava whitefly and disease outbreaks have contributed to high levels of technical inefficiency among cassava farmers in ECA by reducing cassava yields (Mwebaze et al., 2022).

This paper contributes to our scientific understanding of the adoption process by jointly analysing the decision to adopt ICVs and legume intercropping (LI) to mitigate whitefly pests and diseases among smallholder farmers in Malawi, Tanzania, and Uganda. The results highlight the importance of extension and credit access and their interactions with yield-related characteristics on the farmer's decision to adopt the ICVs and LI. The results show that access to extension is associated with an increase in the attractiveness of yield-improving characteristics. Similarly, we find that access to credit was associated with an improvement in the attractiveness of the yield attributes. These findings are robust because the conclusions are similar across both the ICV and LI technologies in Malawi, Tanzania, and Uganda. This study will help inform the development of appropriate technologies by identifying constraints in production, desirable characteristics, and farmer preferences for certain improved cassava technologies. The rest of this paper is structured as follows: The next section describes the relationship between ICVs and LI, the methods, and the survey instrument used in the study, followed by the results, discussion, and policy implications.

2 | ICVs AND INTERCROPPING SYSTEMS

Intercropping is a powerful strategy to promote a diversified cropping system, creating complementary relationships between crop plants (Duchene et al., 2017). Legumes are a fundamental functional group highly valued for their ecological services in smallholder cassava systems. Estimates suggest that about 30%–50% of the cassava produced in Africa is intercropped (Parmar et al., 2017; Weerarathne et al., 2017). In Malawi, Tanzania, and Uganda, LI is common among farmers seeking to diversify their cropping systems (Koppmair et al., 2017). Short-duration grain legumes, such as common beans, mungbeans, cowpea, and groundnut, are the most common crops intercropped with cassava. While intercropping can provide significant benefits, some conditions are necessary for successful cassava-LI systems. In general, the choice of intercrops and the timing of planting are critical factors in avoiding competition for resources (such as light, water, and nutrients). The biological advantage of intercropping cassava with legumes declines with the legume's growth duration (Mutsaers et al., 1993). Parmar et al. (2017) asserted that the first 6 months are optimal for intercropping before cassava develops its canopy.

Compatible intercrops can significantly affect pest, disease, and weed suppression in smallholder cassava production systems. Since plant pests and diseases are spread by wind, rainfall and soil, adding an intercrop can alter population dynamics by impeding infestation, disease development, and dispersal (Delaquis et al., 2018). Many studies show a beneficial impact of intercropping on CMD, reporting a 10%–40% reduction in disease incidence in diversified plots (Delaquis et al., 2018; Fondong et al., 2002; Night et al., 2011). Uzokwe et al. (2016) reported a lower incidence of CMD and its vector whiteflies (*B. tabaci*) in the Lake Zone, Tanzania, when cassava was intercropped with green gram. Besides the whitefly and associated viruses, weed competition is a significant constraint to cassava yields (Fermont et al., 2010). Uncontrolled weed growth can result in near-total yield loss (Chew et al., 2012). While herbicides can be a cost-effective method for weed control in cassava (Chew et al., 2012), Gianessi and Williams (2011) found that only 5% of smallholder farmers in Africa use herbicide on any crop. By contrast, Weerarathne et al. (2017) found that 30%–60% of the weeds could be reduced by intercropping cassava with other crops, such as legumes.

ICVs can increase cassava's resistance to disease, pests, and environmental constraints, thereby increasing yields (Acheampong et al., 2022). Crop yields have increased by up to 40% due to breeding high-yielding ICVs (Nassar & Ortiz, 2007). The International Centre for Tropical Agriculture (CIAT) released ICVs in Asia that are believed to be the main drivers of Asia's cassava yield increase over the past 40 years (Kawano, 2011). Breeding for traits such as root size, drought tolerance, adaptation to poor soil, and disease resistance has helped improve yield (Acheampong et al., 2022; Alene et al., 2018). However, there is still a diversity of cassava cultivars (both traditional varieties and ICVs) grown by farmers in East Africa because not all cassava traits have been the focus of breeding efforts (e.g., complex traits like cooking time, taste and texture of roots are very cultivar-specific). Furthermore, some traditional varieties have high levels of natural tolerance to certain pest species and diseases, but not all pests and diseases (Katono et al., 2021a; 2021b). Some varieties released to help control CMD and CBSD pandemics may also be suitable hosts for whitefly pests (Kalyebi et al., 2021; Omongo et al., 2022). Therefore, the relative benefit of adopting ICVs with improved potential yield will depend on the specific pest and disease pressure each farmer faces each season and, thus, their ability to realize the potential yield gain in an uncontrolled environment.

Due to these complexities, few studies have attempted to disentangle the relative yield impacts of these two approaches (LI and ICV) when combined or in isolation. Ogola et al. (2013) reported mixed results showing that LI and ICVs decreased cassava's fresh root yield in South Africa. Grain yield was lower (by 19%, 15%, and 26%, respectively, for cowpea, groundnut, and chickpea) under intercropping compared with monocropping. The land equivalent ratios (LER) were greater (41%, 33%, and 46%, respectively, for ICV/groundnuts, ICV/cowpea, and ICV/chickpea intercropping systems) than mono-cropped cassava. The study showed that incorporating legumes into cassava-based cropping systems could improve the

systems' overall productivity. Hidoto and Loha (2013) reported a similar finding from a study to determine suitable legumes in cassava-LI in Ethiopia. They showed that intercropping cassava (traditional varieties) with haricot bean, cowpea, soybean, and mung beans reduced cassava yield by 27%, 37%, 52%, and 50%, respectively. However, it resulted in higher land use efficiencies (82%, 49%, 48%, and 62%, respectively) than for either sole crop. The overall LER was higher when cassava was intercropped with legumes, suggesting higher productivity. These studies indicate that the best combination of LI with ICV may be site-dependent and change depending on the needs and resources of the farmers. A better understanding of the trade-offs between ICV and LI seems necessary to target and increase farmer adoption.

3 | DATA AND METHODS

This study is based on a 2015/2016 cross-sectional survey data collected from a sample of smallholder farmers in Malawi, Tanzania, and Uganda. We used various methods to address the study objectives, including literature reviews, workshops, household surveys, and field observations. The socioeconomic data was analyzed using descriptive statistics such as means, standard deviation, and frequency. In contrast, linear regression and double hurdle models (DHMs) were used to analyze the factors influencing the adoption of ICV and LI. This section details the survey data and econometric modeling approaches used in the study.

3.1 | Study areas

The study was conducted in Malawi, Tanzania, and Uganda and focused on districts with high cassava whitefly populations and communities most affected by CMD and CBSD outbreaks. We targeted areas with similar biophysical and Socioeconomic characteristics to allow the identification of a clear causal influence and effects on households. The study involved designing and developing survey tools, training enumerators, workshops, and pretesting survey tools and questionnaires in the study countries. In Uganda, the study specifically targeted the major cassava-producing districts in the north (Apac), central (Nakasongola and Kiryandongo), and eastern regions (Serere, Tororo, and Kamuli). In Tanzania, the survey covered the districts of Geita, Musoma, Rorya, and Ukerewe. In Malawi, the study targeted the main growing areas in the northern belt along the lakeshore (Karonga, Nkhata Bay, and Nkhatakota) and the central belt (Lilongwe). The distribution of sample households across selected regions is shown in Supporting Information S1: Tables A1–A3.

3.2 | Sampling procedure and data collection

Data and information used in this study were obtained from primary and secondary sources. The primary data were collected from a sample of 1200 cassava farmers in Malawi, Tanzania, and Uganda. A multistage random sampling procedure was used to collect data. In the first stage of the sampling procedure, six districts in each country were purposively selected based on their cassava production statistics in past years. Each district was assigned an equal number of sample households. The second stage was the random selection of 4–6 villages within the selected districts and the random selection of 50 cassava households per village. This gave 1200 households: 450 in Uganda, 400 in Malawi, and 350 in Tanzania. The sampling strategy used ensured an unbiased and representative sample of the population of cassava producers in the study countries. We generated the sampling frame from which farmers were selected randomly from a list of farmers obtained from the district agricultural officers in each country. The distribution of sample households across communities in each country is shown in Supporting Information S1: Appendix 1–3. It was

desirable to have a sample representative of all cassava farmers in the country for generalization. We used sampling weights specified as the inverse of the probability of inclusion of the observations to fit the regression models (Cameron & Trivedi, 2010).

Data were collected using a pretested structured questionnaire completed during face-to-face interviews by trained enumerators and extension staff with individual farmers.³ Respondents were interviewed by appointment, which was made through the district extension workers and contact farmers. Pretesting was conducted using 20 farmers in each country to assess the suitability of the questionnaire. Data collected included Socioeconomic characteristics of respondents such as age, gender, education levels, household income, and cassava production, such as acreage under cassava, output, and cassava variety used. The respondents were provided additional information, including color pictures of the cassava whitefly pests and diseases with associated symptoms, to minimize potential bias from farmers' self-assessments. Field observations supplemented information obtained from interviews. The final surveys were conducted during October 7–31, 2015, in Uganda and Malawi and August 15–21, 2016, in Tanzania. The survey was completed on average in 2–3 h per respondent. It was reviewed and approved by the CSIRO Ethics Committee before its release in 2015 and 2016.

3.3 | Descriptive statistics

Table 1 summarizes the descriptive statistics for the sample used in the final model. Overall, these statistics suggest that the sample was representative of the general profile of farmers in the study countries. A comparison with national statistics for Malawi (National Statistical Office [NSO] [Malawi] and ICF, 2017), Tanzania (National Bureau of Statistics NBS, 2017), and Uganda (Uganda Bureau of Statistics [UBOS], 2021) indicates that the sample age, education, and household size were not significantly different to that of the general population. Concerning institutional factors, most cassava farmers lacked access to credit, and only 40% were members of a farmer's organization. The differences in institutional factors among the study countries may also explain adoption rates. For example, looking at Table 1, more of the sample in Malawi has access to extension versus Uganda, where more have access to credit; in Malawi, despite a high population density, farmers tend to be farther from roads compared to Uganda. This suggests there may be reasons to test if these differences impact the influence of characteristics on demand that is worth identifying. More statistics on ICV adoption levels are provided in Supporting Information.

3.4 | Empirical strategy

A linear regression model was used to estimate the determinants of adoption and intensity of ICV and LI in the study countries. One advantage of using the ordinary least squares (OLS) method is that it allows researchers to check the coefficient stability of the results and test for the potential influence of omitted variables, which are a significant limitation to the identification of causal effects (Diegert et al., 2022; Oster, 2019). We begin with the following model specification:

$$Y_i = \beta X_i + \varepsilon_i, \quad (1)$$

where: Y_i is the outcome variable (adoption of ICVs and LI); X_i is a vector of explanatory variables of interest; β is the vector of coefficients to be estimated, and ε_i is error term assumed to be normally distributed with constant variance and zero mean. The main outcome variables are: (1) the adoption

³The survey was conducted by staff from the CSIRO in collaboration with the respective countries' national agricultural research institutions. These included the National Root Crops and Resources Research Institute in Uganda, Mikochei Agricultural Research Institute and Agricultural Research Institute Ukiriguru in Tanzania, and the Department of Agricultural Research Services in Malawi.

TABLE 1 Descriptive statistics of the sample.

Variables	Malawi (n = 400)	Tanzania (n = 350)	Uganda (n = 450)	Pooled (n = 1200)
Variety attributes				
Early maturity	0.75 (0.43)	0.67 (0.47)	0.57 (0.50)	0.66 (0.47)
Cooking quality	0.57 (0.50)	0.35 (0.48)	0.64 (0.48)	0.52 (0.49)
Yield	0.92 (0.27)	0.69 (0.46)	0.80 (0.40)	0.80 (0.38)
Big root size	0.61 (0.49)	0.51 (0.50)	0.49 (0.50)	0.54 (0.50)
Pest and disease resistance	0.30 (0.46)	0.21 (0.41)	0.36 (0.48)	0.29 (0.45)
Yield attribute (combined)	0.98 (0.15)	0.86 (0.35)	0.91 (0.29)	0.92 (0.26)
Socioeconomic characteristics				
Age (years)	47.41 (15.16)	51.09 (13.49)	46.06 (14.65)	48.18 (14.43)
Male household head (%)	65	80	76	73.67
Education of HHD (years)	5.88 (3.38)	8.72 (5.95)	8.13 (4.13)	7.58 (4.48)
Household size	6.32 (2.65)	7.52 (3.75)	8.56 (3.91)	7.47 (3.44)
Farm characteristics				
Farm size (acres)	2.69 (1.97)	4.26 (3.54)	9.84 (20.10)	5.60 (8.54)
Proportion of land under improved cassava variety (%)	9.14 (16.76)	54 (35)	53.88 (38.46)	39.00 (30.10)
Improved cassava variety (1/0)	0.51 (0.50)	0.11 (0.31)	0.70 (0.57)	0.44 (0.43)
Intercropping system (1/0)	0.36 (0.47)	0.71 (0.45)	0.30 (0.46)	0.46 (0.46)
Income from cassava (US\$/acre)	70.40	149.42	84.80	101.54
Institutional characteristics				
Access to credit (%)	16	22	33	23.67
Member of organization (%)	34	43	47	41.33
Access to extension services (%)	45	31	28	34.67
Extension visits	5.39 (6.03)	3.48 (4.24)	2.62 (2.03)	3.83 (4.10)
Distance to nearest roads (km)	2.55 (16.71)	2.70 (15.95)	1.29 (4.38)	2.18 (12.35)
Distance to market (km)	4.86 (25.39)	4.56 (12.19)	4.66 (5.73)	4.69 (4.44)
Land tenure				
Freehold (dummy)	0.09 (0.29)	0.38 (0.49)	0.28 (0.45)	0.25 (0.41)
Leasehold (dummy)	0.01 (0.10)	0.01 (0.09)	0.04 (0.19)	0.02 (0.13)
Customary (dummy)	0.87 (0.34)	0.59 (0.49)	0.62 (0.49)	0.59 (0.43)
Others (dummy)	0.03 (0.17)	0.03 (0.16)	0.06 (0.23)	0.04 (0.20)
Livestock ownership (%)	85	89	97	90.33

Note: Figures in brackets are standard deviations. HHD means household head. Improved cassava varieties and intercropping were measured as categorical/dummy variables using a 1/0 scale.

Source: Field surveys, 2015/2016.

decision (0/1) for the full sample, (2) the amount adopted conditional on adoption (the intensive margin decision for the adopting subsample), and (3) the overall margin-full sample-continuous adoption including the nonadopting 0s. The main explanatory variables are technology characteristics (yield-related attributes), extension, and credit access. Farm and household characteristics and district-fixed effects were included as controls. There was concern that the nuanced differences in yield-related characteristics may cause imprecision in the model estimates of what factors farmers find important. Specifically, models including root size, pest and disease resistance, and yield as three separate variables may lead to inconsistent estimates because the two former traits will lead to the latter. We solved this problem by combining all three into one binary variable (=1 if any of the three is 1).⁴

We implemented the methods Diegert et al. (2022) and Oster (2019) developed to quantify omitted variables bias. These papers defined a set of sensitivity parameters that index relaxations of the assumption that the covariate of interest is not correlated with unobserved variables. We run the following model specification:

$$Y_i = \beta X_i + \gamma_0 W_0 + \gamma_1 W_1 + \gamma_2 W_2 + \varepsilon_i, \quad (2)$$

where: Y_i is the outcome variable (adoption of ICVs and LI); X_i is the explanatory variable of interest; W_0 is a vector of the observed controls, and W_2 is not observed. W_2 is an omitted variable potentially correlated with the variables (X , W_0 , W_1). The parameter of interest is β_{long} , the coefficient of the covariate of interest in the infeasible regression that includes the unobserved variables. Since the methods developed by Diegert et al. (2022) require a single “treatment” variable, we selected extension as the primary variable of interest, while the other variables were used as control variables to help identify the causal effects of extension in the model. Three scalar sensitivity parameters are of interest, denoted as (rX, c) . Given the joint distribution of the observed variables and values of the sensitivity parameters, Diegert et al. (2022) illustrate how to calculate the upper and lower bounds of the identified set for the coefficient of interest, denoted by $\beta_L(\bar{r}_X, \bar{r}_y, \bar{c})$. We also implemented the sensitivity analysis in Oster (2019), which uses different sensitivity parameters. Readers should consult Diegert et al. (2022) and Oster (2019) for more details about the sensitivity analysis.

As a robustness check, we estimated the DHM proposed by Cragg (1971) to investigate the factors affecting the intensity of the adoption of ICV and LI. This method is widely applied in empirical adoption studies (e.g., Awotide et al., 2014; Kondo et al., 2020; Opata et al., 2021; Singbo et al., 2021). The model assumes that farmers make two different decisions, the decision on whether to adopt or not the ICVs and LI (the first hurdle) and the decision on how much to adopt the ICVs and LI (the second hurdle), and that the explanatory factors of these decisions may differ (Burke, 2009, 2019; Wooldridge, 2010). The DHM relaxes the restrictive assumption of the Tobit model, which assumes that the decisions on whether or not to adopt the ICVs/LI and how much to adopt are made jointly, and therefore, the factors affecting the two decisions are assumed to be the same in the Tobit model (Burke, 2009). We provide a detailed description of the DHM in Supporting Information.

4 | RESULTS AND DISCUSSION

4.1 | Determinants of adoption of ICV and intercropping

This section presents the results of the OLS adoption models of ICV and LI pooled across the study countries. The full estimation results for each study country separately are shown in the supporting

⁴Correlation tests confirmed positive correlations among the three variables. We thank the reviewers for this observation which has led to more consistent and statistically significant coefficient estimates.

information (Supporting Information S1: Tables A2–A4). Tables 2–3 present the results of the OLS models using the pooled data for ICV and LI in the study countries, respectively. The R-squared values suggest the models provide a reasonable fit for explaining the relationship between adoption and the explanatory variables. Several variables related to farm and socioeconomic characteristics

TABLE 2 Coefficient estimates of the linear (OLS) regression model of improved cassava variety (ICV) adoption in Malawi, Tanzania, and Uganda (pooled).

Variables	Pooled model		
	Adoption decision (1)	Intensive margin (2)	Overall margin (3)
Technology characteristics			
Early maturity	0.20 (0.04)***	0.01 (0.03)	0.13 (0.03)***
Yield	0.06 (0.08)**	0.12 (0.07)**	0.04 (0.06)*
Cooking quality	0.03 (0.03)	0.03 (0.02)	0.01 (0.03)
Institutional variables			
Group membership	0.07 (0.03)**	0.03 (0.02)	0.09 (0.04)**
Extension	0.04 (0.12)**	0.35 (0.18)**	0.06 (0.15)**
Credit	0.45 (0.17)***	0.48 (0.18)**	0.05 (0.11)
Yield × extension	0.15 (0.13)**	0.40 (0.18)**	0.03 (0.15)**
Yield × credit	0.44 (0.17)**	0.45 (0.17)**	0.08 (0.10)**
Farm characteristics			
Farm size	0.07 (0.02)**	0.19 (0.02)***	0.15 (0.02)***
Freehold ownership	0.06 (0.08)	0.06 (0.07)	0.08 (0.06)
Leasehold ownership	0.08 (0.11)	0.14 (0.09)	0.11 (0.08)
Customary ownership	0.01 (0.07)	0.07 (0.06)	0.07 (0.05)
Socioeconomic characteristics			
Age	0.01 (0.05)	−0.05 (0.04)	−0.03 (0.04)
Education	0.03 (0.03)	0.07 (0.03)**	0.03 (0.02)
Gender	−0.05 (0.04)	−0.01 (0.03)	−0.02 (0.03)
Household size	−0.03 (0.03)	−0.03 (0.02)	−0.03 (0.02)
Livestock	0.04 (0.06)	0.12 (0.06)**	0.09 (0.05)*
Dist. to the nearest road	−0.01 (0.03)	−0.01 (0.02)	−0.01 (0.02)
Dist. to the nearest market	−0.02 (0.02)	−0.02 (0.01)	−0.02 (0.01)
Country dummies			
Malawi	0.68 (0.05)***	0.45 (0.06)***	0.51 (0.04)***
Uganda	0.69 (0.06)***	0.46 (0.06)***	0.52 (0.05)***
Constant	−0.12 (0.22)	0.83 (0.21)***	0.83 (0.17)***
Sensitivity analysis (Oster, 2019)			
$\hat{\delta}_{\text{resid}}^{\text{bp}}$ (%)	46.0	103.8	24.8

TABLE 2 (Continued)

Variables	Pooled model		
	Adoption decision (1)	Intensive margin (2)	Overall margin (3)
Sensitivity analysis (Diegert et al., 2022)			
$\hat{r}_X^{bp}$ (%)	26.9	16.2	10.3
R^2	0.50	0.51	0.52
Obs.	1200	500	1200

Note: Dependent variable is the adoption of ICVs. We use three estimations for the dependent variable—(1) the adoption decision (0/1) for the full sample, (2) the amount adopted conditional on adoption (the intensive margin decision for the adopting subsample), and (3) the overall margin—full sample—continuous adoption including the nonadopting 0 s. Country-fixed effects are included in the pooled models, with Tanzania used as the reference group.

Standard errors in parenthesis. Significance levels:

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Source: Farmer surveys (2015/2016).

have significant effects. We avoid a detailed discussion of all explanatory factors to keep the focus on the impact of the variety characteristics, extension, and credit access on the adoption of ICVs/LI. Results suggest some heterogeneity regarding the factors influencing the adoption decision, intensive margins, and overall adoption margins for ICV and LI in the study countries (Supporting Information S1: Tables A2–A4). Overall, the results indicate that varietal characteristics, extension, and credit access were positively related to the adoption of ICV and LI across the study countries. Early maturity and yield performance coefficients were positive and significantly related to adoption, intensive margins, and overall adoption margins across the study countries. Furthermore, we included interactions to test whether institutional factors increase the attractiveness of the yield-improving characteristics. We found that these differences impact the influence of attributes on demand, which is worth highlighting. Results show that access to extension is associated with an increase in the attractiveness of yield-improving characteristics (Tables 2–3). Similarly, access to credit is correlated to an improvement in the attractiveness of yield attributes. These results provide valuable policy insights to increase technology adoption using a more targeted extension approach. They show that farmers' assessment of the ICV characteristics greatly influences their adoption behavior. Therefore, the omission of farmers' evaluation of technology-specific attributes may bias the results of the factors conditioning adoption choices.

These results are consistent with the literature on consumer demand, showing that demand is affected by product attributes (Mafuru et al., 2008; Miriti et al., 2022; Opata et al., 2021). Farmers are consumers of agricultural research products, and their preferences for the characteristics of new agricultural technologies affect their adoption decisions (Kalema et al., 2022). The findings are similar to those obtained by Adesina and Zinnah (1993) for improved rice varieties in Sierra Leone and Adesina and Baidu-Forson (1995) for improved sorghum and rice varieties in Burkina Faso and Guinea. A more recent study by Kondo et al. (2020) showed that the high-yielding attribute of ICV increased the probability of adoption by 11% in Ghana. In Uganda, Iragaba et al. (2021) found the softness of boiled roots and ground storability as key attributes influencing varietal preference besides yield, disease resistance, early maturity, and drought resistance. In Tanzania, a study by Mafuru et al. (2008) found that the color and taste of sorghum were the most important determinants used by consumers to evaluate the quality of sorghum. Our results suggest that farmers' assessments of variety-specific attributes matter and should be considered in assessing the drivers of adoption decisions of ICVs and LI.

Furthermore, we found a positive relationship between farm size and the intensive and overall adoption margins for both the ICV and LI. This result indicates that farmers with larger farm sizes were more likely to adopt the ICV and LI. Farmers holding a large piece of land are likely to have

more opportunities to learn about new technologies, have more incentives to embrace them and can bear risks associated with new technologies. Adoption also varied by location (See district dummy variables in Supporting Information S1: Tables A2–A4). These results will likely reflect unobservable spatial differences among the study districts or interactions between location and the other

TABLE 3 Coefficient estimates of the linear (OLS) regression model of legume intercropping (LI) adoption in Malawi, Tanzania, and Uganda (pooled).

Variables	Pooled model		
	Adoption decision (1)	Intensive margin (2)	Overall margin (3)
Technology characteristics			
Early maturity	0.08 (0.05)**	0.06 (0.04)*	0.07 (0.03)**
Yield	0.14 (0.09)*	0.15 (0.10)	0.06 (0.02)**
Cooking quality	0.07 (0.04)*	0.06 (0.03)*	0.03 (0.06)
Institutional variables			
Group membership	0.03 (0.04)	0.01 (0.04)	0.01 (0.03)
Extension	0.17 (0.20)**	0.40 (0.14)**	0.13 (0.17)**
Credit	0.22 (0.14)*	0.01 (0.04)	0.21 (0.11)*
Yield × extension	0.21 (0.19)	0.34 (0.14)**	0.01 (0.07)*
Yield × credit	0.33 (0.14)**		0.17 (0.08)**
Farm characteristics			
Farm size	−0.010 (0.03)	0.17 (0.03)***	0.17 (0.02)***
Freehold ownership	0.12 (0.11)	0.10 (0.15)	0.06 (0.06)
Leasehold ownership	0.01 (0.16)	0.07 (0.15)	0.09 (0.08)
Customary ownership	0.04 (0.10)	0.14 (0.14)	0.08 (0.06)
Socioeconomic characteristics			
Age	−0.13(0.06)**	−0.05 (0.05)	−0.06 (0.04)*
Education	0.02 (0.04)	0.03 (0.04)	0.01 (0.02)
Gender	−0.01 (0.04)	−0.04 (0.04)	−0.01 (0.03)
Household size	0.05 (0.04)	0.03 (0.04)	0.02 (0.03)
Livestock	0.02 (0.07)	0.05 (0.07)	0.03 (0.04)
Dist. to the nearest road	−0.02 (0.03)	−0.02 (0.03)	−0.01 (0.01)
Dist. to the nearest market	−0.02 (0.03)	−0.02 (0.03)	−0.01 (0.02)
Country dummies			
Malawi	0.01 (0.10)	0.35 (0.06)***	0.43 (0.04)***
Uganda	0.02 (0.09)	0.36 (0.07)***	0.19 (0.06)***
Constant	0.69 (0.29)**	1.22 (0.29)***	0.73 (0.15)***
Sensitivity analysis (Oster, 2019)			
$\hat{\delta}_{\text{resid}}^{\text{bp}}$ (%)	7.5	39.1	25

TABLE 3 (Continued)

Variables	Pooled model		
	Adoption decision (1)	Intensive margin (2)	Overall margin (3)
Sensitivity analysis (Diegert et al., 2022)			
$\hat{r}_X^{bp}$ (%)	6.59	17.7	16.7
R^2	0.45	0.51	0.53
Obs.	1200	500	1200

Note: Dependent variable is the adoption of LI. We use three estimations for the dependent variable—(1) the adoption decision (0/1) for the full sample, (2) the amount adopted conditional on adoption (the intensive margin decision for the adopting subsample), and (3) the overall margin-full sample-continuous adoption including the nonadopting 0 s. Country-fixed effects are included in the pooled models, with Tanzania used as the reference.

Standard errors in parenthesis. Significance levels:

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Source: Farmer surveys (2015/2016).

identified factors. For instance, the location of farms influences how readily farmers can access information on technologies. Location-specific effects may also affect the acquisition of inputs and credit to expand the area under cultivation (Owusu & Donkor, 2012).

We examined the sensitivity of regression coefficient estimates to the presence of omitted variables. Tables 2 and 3 report estimates of the sensitivity parameters. Based on Oster (2019), the absolute value of the sensitivity parameter delta $|\delta| > 1$ implies limited scope for unobservable variables to explain the results. Based on the $\hat{\delta}_{resid}^{bp}$ estimates, unobservable factors are unlikely to drive our results. Tables 2 and 3 also report estimates of the breakdown point ($\hat{r}_X^{bp}$) developed by Diegert et al. (2022). This statistic represents the largest amount of selection on unobservable factors, as a percentage of selection on observable factors allowed until one can no longer conclude that the coefficient of interest (β) is nonzero. Larger values of $\hat{r}_X^{bp}$ indicate the robustness of the results. The breakdown point estimates in columns (1)–(3) are relatively small, between 10.3% and 26.9%. This implies that we only need the selection of unobservable factors to be at least 10.3%–26.9% as large as a selection of observable factors to overturn the conclusion that the coefficient of extension (β) is zero. Thus, without imposing any restrictions on the impact of unobservable factors on outcomes, we find that the analysis is sensitive to selection on unobservable factors. Supporting Information S1: Figure A5 illustrates one example using the adoption decision estimation for ICV. The solid lines show the estimated identified set for the coefficient of extension (β) as a function of $\bar{r}_X$, allowing for endogenous controls and no restrictions on the outcome equation. The horizontal intercept is the estimated breakdown point $\hat{r}_X^{bp} = 26.9$, as reported in column (1) of Table 2. Overall, while some cases could be considered robust, we find that the results are generally susceptible to omitted variables.

4.2 | Robustness results

As a robustness check, we estimated the DHM to investigate the factors affecting the adoption and intensity of the adoption of ICV and LI. Results of the DHM for the factors affecting the likelihood of adoption and use intensity of the ICV using the pooled data across the study countries are summarized in Table 4.⁵ The full estimation results for each study country are shown in Supporting

⁵The results of the robustness check for LI were very similar to the ICV results and are not reported for brevity purposes.

TABLE 4 Robustness results using the DHM for improved cassava varieties (ICV) in Malawi, Tanzania, and Uganda (pooled).

Variables	Pooled model		
	First part (adoption)	Second part (intensity)	Marginal effects
Technology characteristics			
Early maturity	0.07 (0.13)*	0.13 (0.06)**	0.02 (0.04)**
Yield	0.17 (0.33)*	0.03 (0.13)*	0.07 (0.08)**
Cooking quality	0.15 (0.13)*	0.08 (0.07)*	0.01 (0.04)
Institutional variables			
Group membership	0.03 (0.14)*	0.1 (0.09)*	0.04 (0.05)
Extension	0.19 (0.70)*	0.08 (0.19)*	0.12 (0.05)**
Credit	0.10 (0.73)*	0.10 (0.16)*	0.08 (0.05)**
Yield x Extension	0.03 (0.71)*	0.06 (0.21)**	
Yield x Credit	0.07 (0.74)*	0.10 (0.15)**	
Farm characteristics			
Farm size	0.71 (0.13)***	0.20 (0.08)**	0.03 (0.05)***
Freehold ownership	0.01 (0.16)*	0.15 (0.09)	0.06 (0.06)
Leasehold ownership	0.03 (0.40)	0.04 (0.23)	0.02 (0.13)
Customary ownership	0.42 (0.29)*	0.01 (0.13)	0.08 (0.09)
Socioeconomic factors			
Age	0.24 (0.19)*	0.11 (0.10)*	0.09 (0.06)*
Education	0.23 (0.12)**	0.14 (0.06)**	0.11 (0.04)***
Gender	0.02 (0.14)	0.05 (0.08)	0.03 (0.04)
Household size	0.01 (0.15)	0.09 (0.08)*	0.04 (0.05)
Livestock	0.49 (0.26)**	0.02 (0.23)	0.12 (0.07)*
Dist. to the nearest road	-0.03 (0.09)*	-0.01 (0.04)*	-0.01 (0.03)*
Dist. to the nearest market	-0.05 (0.09)*	-0.02 (0.04)*	-0.03 (0.02)*
Country dummies			
Malawi	0.09 (0.16)**	0.06 (0.09)**	0.05 (0.06)
Uganda	0.10 (0.10)**	0.07 (0.10)**	
Constant	2.68 (0.80)***	-0.67 (0.54)*	
Log pseudolikelihood	-425.17		
Wald χ^2	36.69		
Sigma (σ)		0.45 (0.04)***	
Obs.	1200		

Note: The dependent variable is the observed intensity of adoption of ICVs given as the proportion of land acres allocated to ICVs. Country-fixed effects are included in the pooled models, with Tanzania used as the reference group.

Standard errors in parenthesis. Significance levels:

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Source: Farmer surveys (2015/2016).

Information S1: Table A4. The first-order coefficients, average marginal effects, and measures of fit of the two-part models are shown.⁶ The likelihood ratios of the estimated models are significant at the 1% probability level, indicating the joint significance of the explanatory variables included in the models. Several explanatory variables were again highly statistically significant ($p < 0.05$) as observed in the OLS models. We find similarities and differences in the factors that explain the likelihood of adoption and use intensity of ICVs across Malawi, Tanzania, and Uganda. This justifies using the DHM in examining the adoption of ICVs/LI in this study. Several Socioeconomic characteristics had the expected signs and were significant in explaining adoption decisions. As mentioned, we refrain from a detailed discussion of all influencing factors to focus only on the key variables of interest—variety characteristics, extension, and credit access—and we treat the rest as mere controls.

Varietal traits affect both the adoption and intensity decisions for the ICV, although at different significance levels. This suggests that the characteristics are critical drivers of the likelihood of adoption and use intensity of ICVs/LI, and this finding holds across the three study countries. Yield performance was positively correlated with the probability of adoption and use intensity of ICVs at the 5% level in the combined model. The high yield attribute is associated with a 7% increase in the probability of adopting ICVs, followed by the early maturity period, which is associated with a 2% increase in the likelihood of adoption (Table 4). Furthermore, we found that access to extension is related to the rise in the attractiveness of yield-improving characteristics (Table 4). Likewise, access to credit was associated with an improvement in the attractiveness of the yield attributes. Membership in farmer's organizations was also significantly ($p < 0.05$) related to adopting the ICV. Farm size positively influenced the adoption and use intensity of the ICV at the 5% level across the study countries, suggesting scale effects. An additional acre of land is associated with a 3% increase in the probability of adopting ICVs. This finding implies a scale technology—only farmers with certain land sizes would likely embrace it. The literature shows that ownership of larger farm sizes increases the likelihood of adoption and use intensity of ICVs (Opata et al., 2021). Distance to the nearest market was negatively correlated with the probability of adoption and use intensity of the ICVs/LI at the 5% level across most of the study countries. This suggests that the closer a household is to a market, the higher the likelihood of adopting ICVs. This finding agrees with Kondo et al. (2020) for ICV in Ghana, who reported that differences in households' access to financial and commodity markets significantly influenced technology adoption decisions.

There were also limitations to our study. The adoption of ICV can be affected by other factors, such as profitability and risk associated with technology adoption (Michler et al., 2019), which were not considered here. Future studies should examine the profitability, risk, environmental, and welfare implications of ICV and LI adoption (e.g., see Suri & Udry, 2022 and Michler et al., 2019 for recent analyses of technology adoption in Africa). Our results were generally sensitive to omitted variables. It would be interesting to explore further the implications of omitted variables on technology adoption in future empirical work.

5 | CONCLUSIONS AND POLICY IMPLICATIONS

This study investigated the factors that affect the adoption of ICV and LI among smallholder farmers and provided guidance on the best ways to increase adoption. Our results highlight the importance of technological characteristics and institutional factors in farmers' decisions to adopt ICVs and LI. Technology characteristics, such as yield and early maturity, are critical drivers of adoption behavior. Access to extension is associated with an increase in the attractiveness of yield-improving characteristics. Similarly, access to credit was associated with an improvement in the

⁶The average marginal effects (AME) measure the change in the probability of adoption or the intensity of adoption of the ICV/LI with a marginal change in the variable of interest for continuous variables. For an indicator variable, the AME measures the change in the probability of adoption or intensity of adoption for a discrete change (from 0 to 1) in the indicator variable (Wooldridge, 2010).

attractiveness of the yield attributes. Therefore, varietal attributes must be integrated into ICV adoption dissemination campaigns throughout the study countries. These findings are robust because the conclusions are similar across technologies in Malawi, Tanzania, and Uganda.

These results have important policy implications for future interventions. Firstly, the analysis indicates the need for improved design of extension policies for effective technology promotion to mitigate the threat of cassava whitefly pests and diseases (also see Paul et al., 2022). These measures should include targeting technologies and practices that work together to increase productivity and disseminate information about cassava pest and disease management. Farmers should be given more frequent education and training on technology adoption, especially concerning ICVs and pest management (see Chipeta et al., 2016). Governments should expand the current efforts by local and international nongovernmental organizations (such as the World Bank, the Bill & Melinda Gates Foundation, FAO, UK DFID, Feed the Future Initiative by USAID, NEPAD Pan African Cassava Initiative, etc.) to develop sustainable, market-oriented ICV seed systems for smallholder farmers in Malawi, Tanzania and Uganda. Ongoing field trials by the respective countries' national agricultural research institutions to develop ICVs resistant to the cassava whitefly and diseases and high yielding should be expanded in the study countries.

The results affect ICV research and development in ECA. They show that the yield performance of ICVs needs to be evaluated by farmers under their field conditions. Varieties that farmers judge as having superior yield performance over local varieties under their farm conditions tend to be adopted. Farmers are also important sources of technology information and agents of technology transfer. When farmers evaluate the characteristics of new ICVs and find them to match their preferences, they often give the ICVs to other farmers for assessment, thereby setting into motion a dynamic technology adoption process (Grisley, 1994). The low adoption levels of ICVs in ECA suggest a lack of markets where farmers can sell their surpluses. Increased yield gains will likely not be attractive for cassava farmers without additional economic profits, which require markets for surpluses (see Michler et al., 2019). This implies that focusing policy solely on ICV yield gains may be insufficient to motivate adoption. Incorporating traits other than yields and improving households' ability to generate higher returns (through complementary investments that will enhance cassava value chains and market access) should accompany ICV yield-increasing programs in Malawi, Tanzania, and Uganda. The adoption of ICV is likely to increase with improved market access. Our results imply that the government should support local institutions and service providers in the presence of market failure since they effectively support farmers by providing credit, inputs, information, and market outlets.

Finally, governments and NGOs should encourage and support local, national, regional, and international exchange of experience, skills, and technologies. We recommend field trials to replicate good examples of optimized cassava production in other countries (e.g., Ivory Coast with no viruses, no bacteria, clean cuttings, high density, no weeds, optimal management, and 60 t/ha yields). There are lessons for the cassava sector in ECA based on policy responses undertaken by the Government of Thailand (e.g., Tijaja, 2009). The Thailand cassava sector grew partly due to government support for domestic research and development. Thailand actively supported research institutions to promote ICVs, farmer training, and participation in policy dialogs, and they implemented policies to encourage trade and agribusiness (Tijaja, 2009). The organization's focus on increasing yield, market access, and attracting investors can be directly linked to growth in the cassava sector. Similar sector-wide initiatives could deliver benefits for East African small-holder farmers.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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