Discover Agriculture

Research

From organic farming to agroecology farming, what challenges do organic farmers face in Central Uganda?

Bienvenu Akowedaho Dagoudo[1,3] · Charles Ssekyewa[1,2] · Joseph Ssekandi[1] · Khady Ngom[1] · Hellen Naigaga[1] · Ismail M. Moumouni[3] · Kandioura Noba[4]

Received: 3 March 2024 / Accepted: 25 June 2024
Published online: 16 July 2024

Abstract
Revealed as a production system that does not use synthetic fertilizers or pesticides, organic farming is recognized as ecological production and has been institutionalized in Uganda. Organic production continues to face the challenges of what is considered agroecology farming, which is viewed nowadays as an opportunity for creating new value chains and food systems for agricultural production based on protecting the environment and supplying nutritious and safe foods to society. This paper focuses on agroecology farming indicators to assess organic farming in order to highlight the challenges organic farmers face in implementing agroecology practices. The data collection was carried out in 5 districts in Central Uganda: Wakiso, Masaka, Bukomansimbi, Ssembabule, and Kyotera. A multiple-stage stratified sampling was used to select 310 organic farmers in 5 districts. Various representations and correlation analyses of agroecology indicators have been conducted using descriptive statistics and correlation tests. The findings show that 51.9% of organic farmer respondents have at least three crops produced in the local climate for a long time, and 58.71% of organic farming has medium integration (animal feed is mostly self-produced and grazed, and their manure is used for compost and fertilizer). It highlights that seeds and animal genetics are self-produced, neighbor farms exchange them, and some specifics are purchased at local markets for 51.61% organic farming. The results revealed that 61.61% of organic farms visited had half of the arable soil covered with organic residues. The correlation test revealed that there is a significant positive correlation between diversity animal genetics and crop and livestock integration ($r = 0.674$, $p < 0.01$), between harvesting and saving water systems and resilience and adaptability to climate variability ($r = 0.546$, $p < 0.01$), and between diversity crops and diversity activities and services ($r = 0.523$, $p < 0.01$). Despite the interdependence of organic farming's agroecology practices, most residues and waste are not recycled or reused as organic fertilizer, and organic farmers have limited equipment to harvest and save water for production. This is an opportunity for organic stakeholders to invest in organic residues and waste recycled equipment in order to create a new value chain for organic production by producing organic fertilizers and biopesticides.

Keywords Organic farming · Agroecology farming · Organic farmers · Agroecology indicators · Uganda

✉ Bienvenu Akowedaho Dagoudo, akowedahobienvenu@gmail.com | [1]Faculty of Agriculture, Uganda Martyrs University, Nkozi, P.O. Box 5498, Kampala, Uganda. [2]St. Lawrence University, Mengo, P.O.BOX 24930, Kampala, Uganda. [3]Department of Rural Economics and Sociology, Faculty of Agronomy, University of Parakou, BP 123, Parakou, Benin. [4]Department of Plant Biology, Faculty of Sciences and Techniques, Cheikh Anta Diop University, Dakar, Senegal.

1 Introduction

Agriculture is a complex activity that combines providing food for human beings with protecting the stability of biotic and abiotic elements in a natural ecosystem. However, the introduction of the new input (chemicals) leads to the instability of this ecosystem through damage to the biotic and abiotic elements that contaminate the foods for human beings. For decades, the agriculture sector in the majority of African countries relied on local resources interlinked with indigenous knowledge [1]. This included the biology and genetic varieties produced by small farmers in order to maintain robust and resilient practices and reduce the damage caused by pests, diseases, and climate variability [2]. Considered unprofitable, some companies introduced intensive agriculture through the intensive use of chemical fertilizers, pesticides, and land as a reason to increase the production per unit of product and cash [3]. Supported by the green revolution, intensive agriculture causes damage to the environment and biodiversity associated with traditional knowledge loss and the debt of many poor farmers because of their dependence on external inputs such as synthetic fertilizers, pesticides, and some specific seeds [4]. Green revolution promotes conventional agriculture, where production systems are highly dependent on the overuse of water, chemical fertilizers, and pesticides [5, 6]. In contrast to the green revolution, organic farming focuses on regular organic inputs, the use of manure and compost as fertilizers, and rotation and intercropping practices [7]. Organic farming practices prohibit synthetic product utilization such as herbicides, insecticides, fungicides, acaricides, mineral nitrogen, superphosphate, and potassium chloride fertilizers [8]. Therefore, organic farming approaches replace synthetic inputs with ecological endogenous inputs [9, 10]. Organic farming constitutes the way to provide healthy and safe foods to the population, protect agrobiodiversity, and assure food sovereignty. Organic farming is the foundation of ecological conservation, biodiversity, and cycles adapted to local conditions that combine traditional knowledge and innovation to protect the environment and promote equity in relationships between quality of life and all involved. In Uganda, 139,191 agricultural producers are involved in organic production, with 16,376 ha harnessed for organic production [11]. Can organic farming be considered agroecology farming?

As well as organic agricultural production protecting the environment, promoting agrobiodiversity, and restoring soil fertility by avoiding synthetic chemical utilization, there is no evidence it can be considered an agroecology farming. For Dagoudo et al. [12], organic agriculture, which emphasizes fairness, care, health, and ecological principles in agricultural production, serves as the foundation for agroecological practices. Agroecology provides indicators that embrace innovations, diverse practices, and farming landscapes for increasing biodiversity, nurturing soil health, improving recycling, promoting ecosystem services, and stimulating interactions between species, etc. Agroecology farming refers to the agricultural practices that encompass diversity in the cultivation of different varieties of seeds, biological diseases, pest control through intercropping and agroforestry, recycling of residue and waste for soil protection and fertilization, and biodiversity conservation, etc. [13, 14]. However, agroecology as science try to address the root causes of agriculture problems for system transformation, following a holistic approach and finding sustainable solutions [15] that consider the complexity of farming systems within the social, economic, and ecological local contexts [16]. Organic farming is recognized through organic production in Uganda [11]. However, what are the challenges faced by organic farmers in implementing agroecology practices such as diversity, synergies, recycling, and resilience? The paper aims to assess organic production in Central Uganda using agroecological practices indicators (diversity, synergies, recycling, and resilience) in order to reveal the challenges facing organic farmers in implementing agroecology practices. This paper is segmented as follows: after the introduction, follow the methodology, which encompasses the study area and data collection and analysis. The study area describes the districts selected in Central Uganda for the research, and the data collection and analysis focus on sampling and agroecological indicator assessment. After the methodology, we have the results, which present the findings following the discussion. The conclusion depicts the particularity of the research, and at the end are the recommendations.

2 Relationship between organic farming and agroecology farming

Organic farming incorporates natural landscape elements into agricultural production that concentrates solely on organic agriculture. According to [17], organic agriculture is defined as a production system that sustains the health of soils, ecosystems, and people. It is based on ecological processes, biodiversity, and cycles tailored to local conditions, rather than the use of harmful inputs. Organic Agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved. Organic agriculture is founded on four principles, which are: fairness, care, health, and ecology [17]. The four principles of organic farming are described as follows:

- *The Health aspect involves* sustaining and enhancing the health of the soil, plants, animals, humans, and the planet as one and indivisible;
- *Ecology* is based on living ecological systems and cycles, work with them, emulate them, and help sustain them;
- *The fairness* aspect builds on relationships that ensure fairness with regard to the common environment and life opportunities and;
- *Care* focuses on managing in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

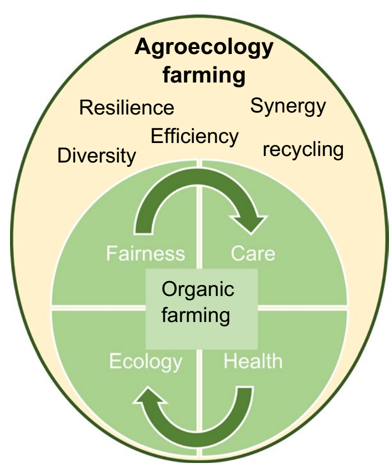
Agroecology aims to redesign the entire food system, encompassing the ecological, economic, and social dimensions of sustainability [18], through transdisciplinary, participatory, and change-oriented research and action [19]. Agroecology is an ecology-based discipline defined by five principles: diversity, synergies, efficiency, recycling, and resilience [18, 20–23]. Agroecology farming, based on organic farming, improves agricultural systems by regenerating beneficial biological integration and interactions amongst the natural components of agroecosystems and enhancing natural processes and ecosystem services for food systems. Agroecology as a science focuses on diversity, efficiency synergies, recycling, and resilience [18, 20–23] as criteria to assess health, ecology, fairness, and care in organic farming. Thus, organic farming incorporates agroecology, which can be evaluated using agroecology indicators. Figure 1 presents the relationship between organic farming and agroecological farming.

3 Methodology

3.1 Study area

The research was conducted in Mukono zonal agricultural research and development, which includes Central Uganda. [24]. In central Uganda, five districts, such as Wakiso, Masaka, Bukomansimbi, Ssembabule, and Kyotera, were chosen to carry out the data collection (Fig. 2). The zonal agricultural research is the second in Uganda with 1,382,610 Agricultural Households [24]. This study area is characterized by a tropical climate with bimodal rainfall patterns with two rainy seasons: the first season (March to May with a peak in April) and the second season (October to December with a peak in November). The mean annual rainfall is 1614 mm. The temperature averaged between 18.14 and 26.53 °C; however, the years 2015 to 2020 registered an annual average of minimum 18.5 °C and maximum 28.1 °C [24, 25].

Fig. 1 Organic farming and agroecology farming



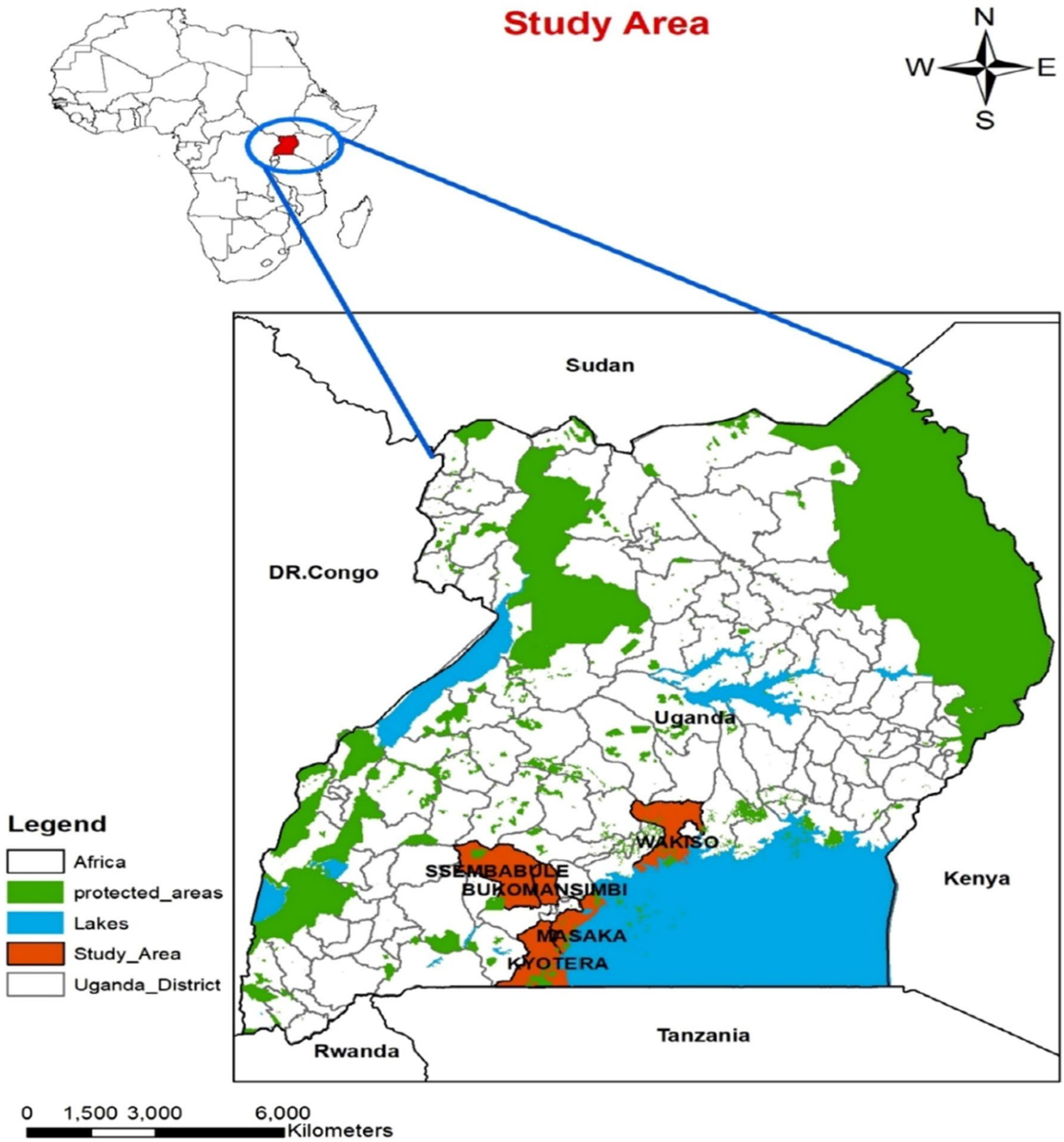


Fig. 2 Study area

3.2 Data collection

The data collection was focused on organic farmers in central Uganda. Organic farmers were recognized for applying some agricultural practices that involved agroecology principles such as diversity, resilience, recycling, and synergies, and system production was mostly characterized as rain-fed production systems. According to Food Security and Nutrition (FAO), recycling, diversity, resilience, and synergies are central ecological features of agroecology [26]. Organic farmers were purposively sampled through the multiple-stage stratified sampling procedure. Organic farmers who took part in this data collection are members of the Participatory Guarantee System (PGS) group, which is recognized by the National Organic Agriculture Movement of Uganda (https://nogamu.org/). A sample of 310 organic farmers was purposefully selected for interviews using the multiple-stage stratified sampling procedure. The data gathered emphasized agroecology practices that indicated diversity, resilience, recycling, and synergies in organic farms and their production outcomes. The farm visit is essential for collecting agroecology data through interviews and participatory observation. The multiple-stage stratified sampling procedure is summarized as follows:

- First, two institutions that are members of Uganda's National Organic Agriculture Movement and have at least 20 years of experience expanding organic production practices were chosen. The two institutions were the Agency for Integrated Rural Development (AFIRD) and the St. Jude Family Project.
- Secondly, in each institution, the study zone was purposively selected according to experience in organic production practice (at least 5 years). For AFIRD, Wakiso district was selected, and for the St. Jude Family Project, Bukomansimbi, Ssembabule, Kyotera, and Masaka districts were selected.
- Third, organic farmers who took part in this data collection were chosen at random from organic farmer groups recognized by the National Organic Agriculture Movement of Uganda in each district. The availability of organic farmers during the data collection period is also critical for sampling data collection.

The data collection is limited only to agroecology practices (diversity, resilience, recycling, and synergies) on organic farms, and the number of organic farmer respondents is not exhaustive in the area study but representative of statistical tests. Table 1 presents the number of organic farmers interviewed per district and institution.

Figure 3 depicts the sampling approach used in the research.

The survey was carried out in December 2022 and February 2023. The organic farmer respondents at least deposited the document with the National Organic Agriculture Movement of Uganda (NOGAMU) to be certified, or they already have organic certification. NOGAMU is an umbrella organization that unites producers, processors, exporters, NGOs, and other institutions and organizations that are involved in the promotion and development of the organic sector in Uganda. The two NOGAMU member institutions selected for this research were:

- AFIRD (Agency for Integrated Rural Development), which is a non-government organization registered under number No: S-5914/2404 and certificate No: 2222 in 1998. They implemented some rural development projects in which their actions consisted of training the farmers in organic sustainable practices through farm planning, soil protection, and water harvesting, the integration of animals into the farming system, and vegetable growing using indigenous seeds.
- The St. Jude Family Project, which was created by Josephine Kizza and her late husband, John Kizza. It is located in Masaka district, registered under number No: S.5914/2000. The St. Jude Family Project focuses on local farmers conditions through training and support in organic farming and agroecological practices. The local farmers are mostly women farmers' groups, youth, and schools.

The data collection was carried out in accordance with relevant guidelines and regulations that were approved by AFIRD institution and St. Jude Family Project institution.

Table 1 Number of organic farmers interviewed

Institution	District	County	Number of organic farmers	Total	Percentage
Agency For Integrated Rural Development	Wakiso	Busiro	50	200	64.52
		Nansana Municipality	50		
		Kyadondo	50		
		Kira Municipality	50		
St. Jude Family Project	Bukomansimbi	Bukomansimbi	30	110	35.48
	Ssembabule	Mawogola	27		
	Kyotera	Kyotera	27		
	Masaka	Bukoto	26		
Total				310	100

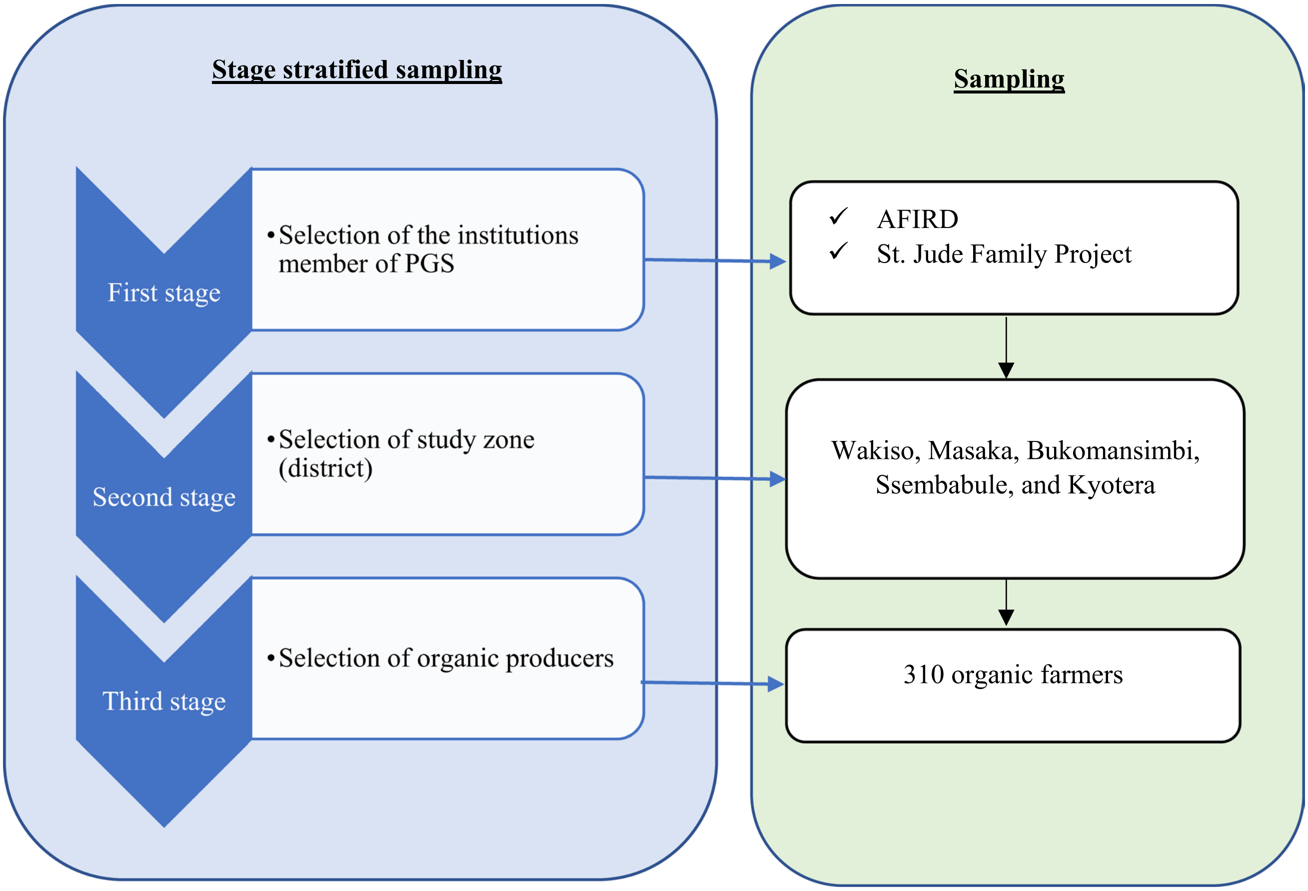


Fig. 3 sampling approach

3.3 Data analysis

The analysis of organic farming through agroecological approaches was based on the Tool for Agroecology Performance Evaluation (TAPE) developed by FAO [26]. The method implemented is determining the score for the agroecological indicators. For each indicator, appropriate attribution of the scores was based on interviews and organic farm observation. According to the conceptual framework (Fig. 1), agroecological indicator efficiency will be considered a transversal

Table 2 Agroecology indicators

Principle	Indicator	Score
Diversity	Crops	0 to 4
	Animal species	
	Activities and services	
Synergy	Integration of crop and livestock	0 to 4
	Soil protection system by plants	
	Agroforestry and silvopastoralism practices	
Recycling	Biomass and nutrients recycled	0 to 4
	Harvesting and saving water system	
	Seeds and animal genetic autonomy	
Resilience	Income stability and recovery capacity from climate shocks or perturbations	0 to 4
	Resilience and adaptability to climate variability	

Table 3 Indicator variables

Principle	Indicator	Score	Variables
Diversity	Crops	0	Monoculture (or one crop cultivated)
		1	One crop occupies more than 80% of farmed land
		2	Two or three crops have been produced
		3	More than 3 crops have been produced in local climatic for a long time
		4	Significant of crops varieties have been produced with multi-, poly- or inter-cropping
	Animal species	0	Zero animals raised
		1	One species of animal raised
		2	Several different animal species were raised
		3	Several different animal species were raised with a few varieties of genetics
		4	Several different animal species were raised with high varieties of genetics
	Activities and services	0	Only one activity exerts
		1	Two or three activities exert
		2	More than three activities plus one service
		3	More than three activities plus more than one service
		4	Significant number of activities and services
Synergy	Crop and livestock integration	0	Animals are fed by-products purchased in the local market, and manure is not used
		1	Animals are mostly fed by-products purchased in the local market; the manure serves as organic fertilizer
		2	Animals are mostly fed by-products from their own farms and grazing, and the manure serves as fertilizer
		3	Crop residues are used to feed animals and some grazing, and the manure mostly serves as fertilizer
		4	Crop residues are exclusively used to feed animals and grazing, and all manure serves as fertilizer
	Soil protection systems by plants	0	No soil protection systems by plants, Soil is bare after harvest
		1	The crop leftovers cover less than 20% of the land cultivated with monoculture practices in the rest of the land
		2	The crop leftovers cover half of the arable land with rotation crops and intercropped practices
		3	More than 80% of arable land is covered by crop leftovers with regular crop rotation and sometimes intercropping
		4	All the land cultivated is covered by crop residues with regular crop rotation and intercropping
	Agroforestry and silvopastoralism practices	0	No trees and perennials crop on a farm
		1	Presence of a small number of trees and perennials crops
		2	Presence of a significant number of trees and perennials crops
		3	A significant number of trees and perennials crops provide some organic products and services
		4	Several trees and perennials crops provided several organic products and services

Table 3 (continued)

Principle	Indicator	Score	Variables
Recycling	Biomass and nutrients recycling	0	No recycling of organic farming residues
		1	A small part of organic farming residues is used. Organic waste was discharged or burnt
		2	More than 50% of organic farming residues are used: crop, vegetable, spices, and fruit leftovers are used as animal feed, manure of compost, or fertilizer
		3	Most of the organic farming residues are used. There is a little discharged or burned waste
		4	All organic farming residues are used. There is no waste on the farm
	Harvesting and saving water system	0	No equipment or techniques to harvest and save water
		1	One equipment (drip irrigation or tank) to harvest or save water
		2	One equipment (drip irrigation or tank) to harvest or save water + techniques to reduce water use
		3	One equipment (drip irrigation or tank) to harvest and save water, and some techniques to optimize water use
		4	Several equipment to harvest and save water + some techniques to optimize water use
	Seeds and animal genetic autonomy	0	All organic seeds and animal genetic breeding were provided by external sources
		1	80% of organic seeds and animal genetic breeding were provided by external sources
		2	About 50% of the organic seeds and animal genetic breeding is obtained by exchanging with neighboring farmers
		3	External sources contribute a little to organic seeds and animal genetic breeding; the majority is self-produced or obtained by exchanging with neighboring farmers
		4	All of the organic seeds and animal genetic breeding were self-produced or obtained by exchanging with neighboring farmers
Resilience	Income stability and recovery capacity from climate shocks or perturbations	0	Production is decreasing, resulting in income failure with the constant level of organic inputs used. Any capacity to recover after shocks or perturbations
		1	Production is decreasing with constant input, which entails reducing income. Climate shocks or perturbations can be difficult to recover from
		2	Organic income is declined and production is variable from year to year with constant inputs with good capacity to recovery
		3	Production varies a little from year to year (with constant inputs) with income stable with good capacity to recovery
		4	Over time income and production are increasing with the capacity to recover after shocks or perturbations quickly
	Resilience and adaptability to climate variability	0	Organic farming is highly subjected to climatic shocks without adaptability systems
		1	Organic farming is subjected to climatic shocks but has the system to alleviate climate variability effects
		2	Organic farming is exposed to climatic variability shocks but has a good system to overcome the difficulties
		3	Organic farming is exposed to climatic variability shocks but has a strong system to overcome the difficulties
		4	Organic farming has a strong natural capital base, climatic shocks are rare; and it has a strong system to overcome all difficulties of climate

indicator in organic farming, which means that efficiency can be measured in terms of diversity, synergies, recycling, and resilience. As a result, the data analysis will center on four agroecological indicators: diversity, synergy, recycling, and resilience. The scores of each indicator for diversity, synergies, recycling, and resilience range from 0 to 4, depending on how organic farming is. In terms of scale, the score is to provide an indicator that gives the percentage of organic farms by a range (Table 2). The variables used in data analysis, are based on agroecology indicators (diversity, synergies, recycling, and resilience), are represented in Table 3. The different organic products were represented in word clouds. The word clouds was used to depict the unweighted lists of organic products produced on organic farming respondents [27–29]. The findings will indicate the word clouds of an alphabetically ordered unweighted list and its larger letter sizes, as well as frequently used terms [28–30]. For analysis, the mean, percentage, and standard deviation were used as descriptive analysis, and the Pearson correlation coefficient r as a measure of the significant relationship between diversity, synergies, recycling, and resilience.

4 Results

4.1 Profile of organic farmer respondents

According to the findings of the study, organic farming practices were used by both men (29.03%) and women (70.97%). This means that women are overwhelmingly responsible for spreading agroecological practices in Central Uganda. The results indicated that the organic farmers are schooled at the primary education level (38.710%) and the secondary education level (29.03%). The percentage of education probably has a bearing on understanding the capacity of organic farmers, which is indispensable for some innovations to protect soil and the environment, increase productivity, and manage the integration of crops, trees, and breeding. In organic farming, the householders are composed of on average 6 persons (minimum 1 person and maximum 20 persons) (Table 4). The family size shows the variability of labor availability on organic farms. It is noticed that the average age of organic farmers is 53 years old, ranging between 20 and 90 years. In Central Uganda, on average, 2 male organic farmers and 2 female organic farmers were active in agroecological farming

Table 4 Profile of organic farmers

Variable	Frequency	Percentage
Sex		
Female	220	70.97
Male	90	29.03
Schooling level		
Primary	120	38.71
Secondary	90	29.03
University	32	10.32
Vocational	36	11.61
None	32	10.32
Status		
Married	202	65.16
Widow	59	19.03
Single	31	10
Divorced	18	5.81

	Mean	Std. Dev	Min	Max
Age	53.1	14.16	20	90
Family size	6.34	2.96	1	20
Male actives	1.97	1.22	1	9
Female actives	2.36	1.54	1	14
Size of area organic production (ha)	0.79	0.67	0.04	4.86

Fig. 4 Organic crops

Fig. 5 Organic vegetables

practices in the respondents' households. Meanwhile, organic production is characterized by small holdings, with an average holding size of 0.79 ha (± 0.67).

4.2 Organic crops and vegetables produce

The survey revealed that bananas, coffee, cassava, beans, maize, and yams are the crop most produced organically according to the results of the word cloud (Fig. 4). As regards the vegetables, the organic farmers produced the *Sukuma wiki*, Amaranthus, eggplant, pumpkin, and tomatoes… (Fig. 5).

4.3 Organic fruits and spices produce

The word cloud shows the organic fruits and spices produced by organic farmers. The organic fruits most present on organic farms are avocado, jackfruit, mangoes, pawpaw, pineapple, and orange (Fig. 6). For the spices, we have African basil, rosemary, mint, ginger, lemongrass, and garlic (Fig. 7).

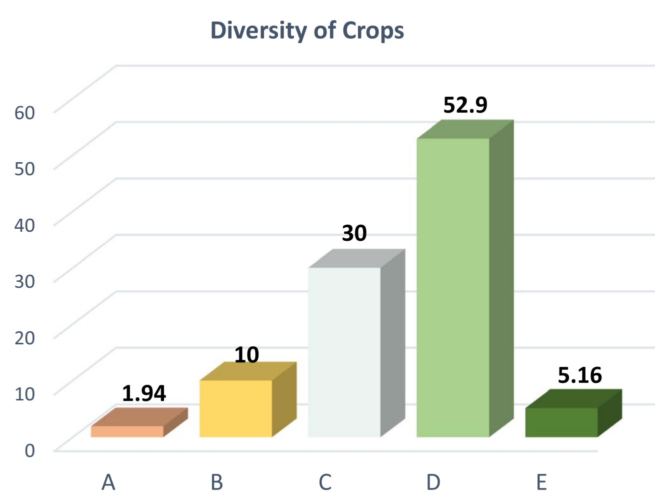
4.4 Diversity

4.4.1 Diversity of crops

Organic crop production in Central Uganda is characterized by rain-feed despite organic farmer efforts for the irrigation system. This exposes organic crop production to risks tied to the variability of the seasonal distribution of rainfall in space and time and its unpredictability. Therefore, organic farming is exposed to climatic events such as floods,

Fig. 6 Organic fruits

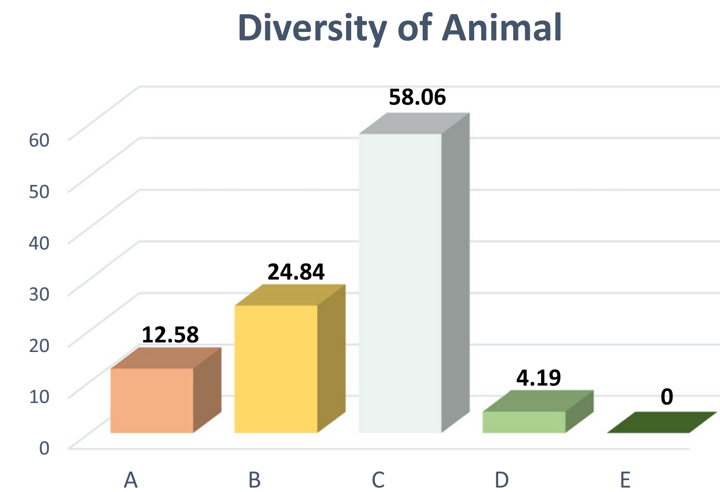
Fig. 7 Organic spices



A	Monoculture (or one crop cultivated)
B	One crop occupies more than 80% of farmed land
C	Two or three crops have been produced
D	More than 3 crops have been produced in local climatic for a long time
E	Significant (at least 6) of crops varieties have been produced with multi-, poly- or inter-cropping

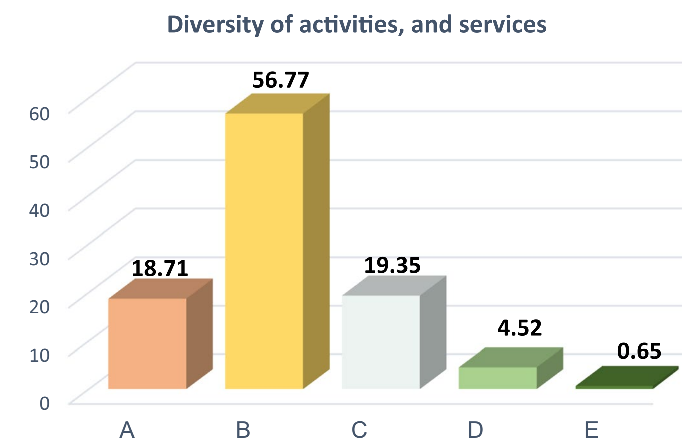
Fig. 8 Diversity of crops

storms, and droughts, which have severe impacts on production and provoke instability in production systems. The findings show that the organic farmers (52.9%) have at least three crops that have been produced in the local climate for a long time (Fig. 8). According to the agroecology indicator assessment scale, crop diversity is significant and contributes overwhelmingly to alleviating the impact of climatic variability.



A	Zero animals raised
B	One species of animal raised
C	Several different animal species were raised
D	Several different animal species were raised with a few varieties of genetics
E	Several different animal species were raised with high varieties of genetics

Fig. 9 Diversity of animal



A	Only one activity exerts
B	Two or three activities exert
C	More than three activities plus one service
D	More than three activities plus more than one service
E	Significant number of activities and services

Fig. 10 Activities, and services diversity

4.4.2 Diversity in animal species

Animal breeding is an important contributor to organic farming and the livelihoods of the farmers through a source of revenue, food (meat), and non-food products like manure and urine. It is also the source for risk reduction during the season of crop failures, investment, and property security, and has many cultural functions such as dowry for marriage and sacrifice. In organic value production, animal breeding is essential for organic manure fertilizer for silvopastoralism, and agrosilvopastoralism. Diverse animals were bred on the organic farm, such as cows, goats, pigs, rabbits, and birds. The findings show that the majority of organic farmers (58.06%) breed several species with few animals (Fig. 9).

4.4.3 Diversity in activities and services

Many activities and services in organic farming are lucrative activities and services on which organic farming depends. Different activities provide different products on the market. It is a potential source of financial resources that can be re-invested in the farm to increase production yield and contribute to farm sustainability. The diversity of activities and services important indicator for an analysis of the vulnerability of organic farmers to natural disasters (storms, drought, flood) which can appear at all times of organic production. According to the scale of agroecology indicator assessment, the majority (56.77%) of organic farmers in Central Uganda have between two and three productive activities and services and are therefore the most vulnerable to natural disasters (Fig. 10).

4.5 Synergy

4.5.1 Crop and livestock integration

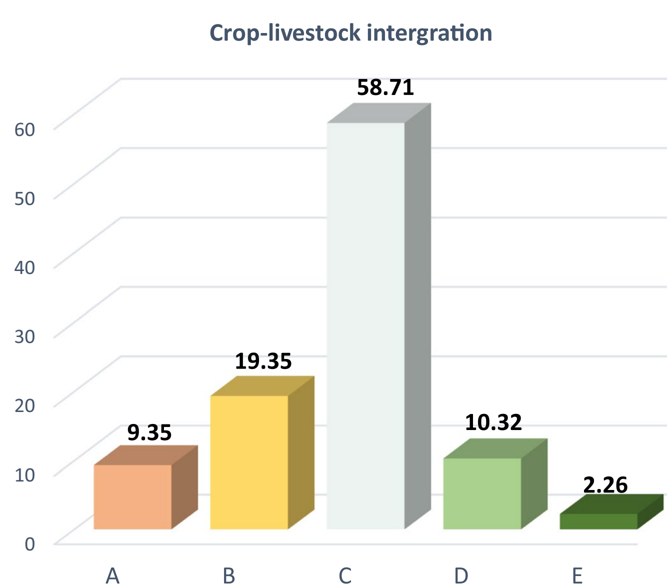
The integration of crops and livestock is a practice that provides organic manure through mixed farming systems and involves complex resource exchanges. It is an important phase of the cycle of interactions between crop and livestock production through animal feeding, manure management, and crop residues. Crop and livestock integration practices are traditional agricultural practices that have been improved in terms of innovation for organic manure and compost. The results revealed that the majority (58.71%) of organic farming has medium integration, which means the animals breeding are mostly fed by farm products and grazing, and the animal manure is used as fertilizer (Fig. 11).

4.5.2 Soil protection systems by plants

Soil protection systems by plants are the key to soil management as regards organic carbon stock, soil, physical properties, biological activity, fertility, water storage, nutrient leaching and runoff, and erosion potential. Soil protection systems by plants focus on the application of crop residues after harvesting to protect the soil. The organic farmers who participated in this research protect half of the soil by covering it with crop residues, with the majority at 61.61% (Fig. 12). Some crops in the farm are rotated or intercropped. The soil protection system is medium according to the scale of agroecology indicator assessment.

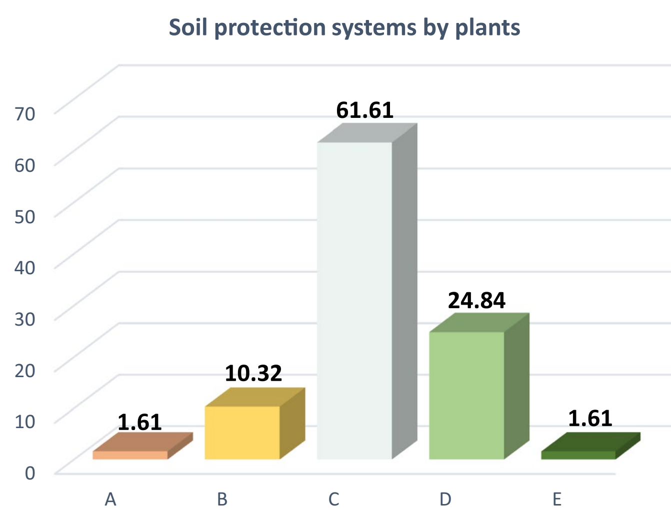
4.5.3 Agroforestry and silvopastoralism practices

Integration of trees (or perennials crops) by organic farmers is beneficial for the production of crops against extreme events in microclimate and soil moisture, and shade tree cover protects crop plants from fluctuation. Organic agricultural production is the most the practice of integrating trees, forage, and the grazing of domesticated animals (silvopastoralism). The grazing of domesticated animals' structures agroecosystems through energy flows, nutrient recycling, and the regulation of other organisms. The integration is medium (significant number of trees (perennials) present in farm provide at least one product or service) in the majority (53.23%) of organic farming (Fig. 13).



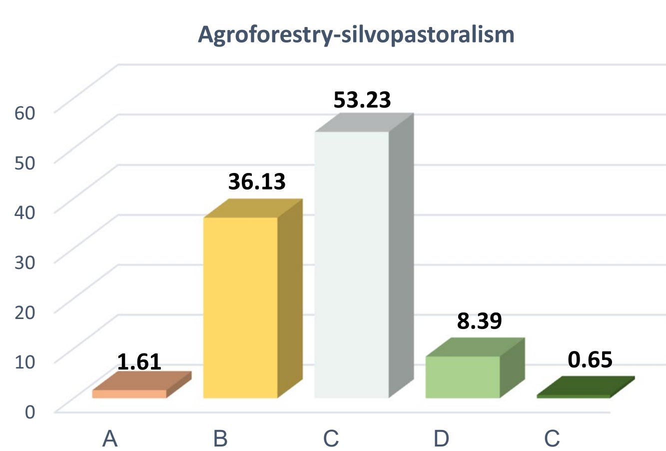
A	Animals are fed by-products purchased in the local market, and manure is not used (no integration)
B	Animals are mostly fed by-products purchased in the local market; the manure serves as organic fertilizer (low integration)
C	Animals are mostly fed by-products from their own farms and grazing, and the manure serves as fertilizer (medium integration)
D	Crop residues are used to feed animals and some grazing, and the manure mostly serves as fertilizer (high integration)
E	Crop residues are exclusively used to feed animals and grazing, and all manure serves as fertilizer (complete integration

Fig. 11 Crop and livestock integration



A	No soil protection systems by plants, Soil is bare after harvest.
B	The crop leftovers cover less than 20% of the land cultivated with monoculture practices in the rest of the land.
C	The crop leftovers cover half of the arable land with rotation crops and intercropped practices.
D	More than 80% of arable land is covered by crop leftovers with regular crop rotation and sometimes intercropping.
E	All the land cultivated is covered by crop residues with regular crop rotation and intercropping

Fig. 12 Soil protection systems by plants



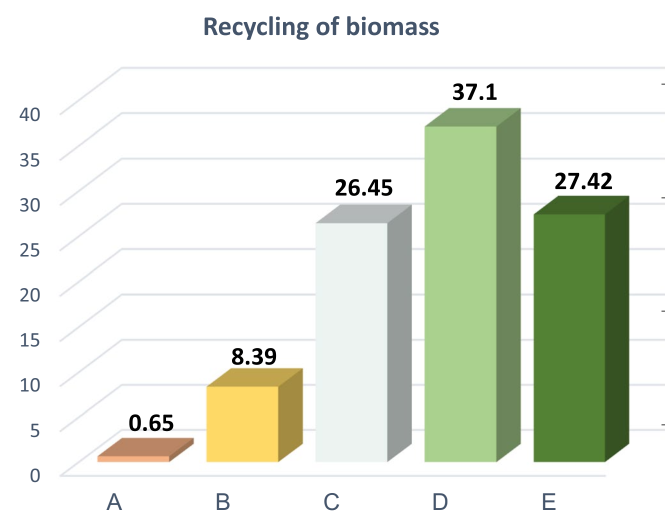
A	No trees and perennials crop on a farm (no integration)
B	Presence of a small number of trees and perennials crops (low integration)
C	Presence of a significant number of trees and perennials crops (Medium integration)
D	A significant number of trees and perennials crops provide some organic products and services (high integration)
E	Several trees and perennials crops provided several organic products and services (complete integration)

Fig. 13 Agroforestry and silvopastoralism practices

4.6 Recycling

4.6.1 Biomass and nutrients recycling

Biomass and nutrient recycling in organic farming determine the regeneration of soil nutrients, which affect water infiltration, holding capacity, and content in the soil and safeguard soil physical properties through soil aeration and permeability. It is the response of soil aggregation and rooting, soil crusting, bulk density, runoff, and erosion. Biomass and nutrient recycling in organic farming involves the important use of manure and household waste to produce compost for fertilizing and crop residues as animal feed. The organic farming biomass and nutrients registered in Central Uganda are composed of residues from crops, vegetables, spices (straws, tops, stalks, leaves, and shoots), and fruits. The results revealed that more than 50% of organic farming residues are recycled which encompasses crop, vegetable, spices, and fruit residues, and be used as animal feed, manure of compost, or fertilizer in 26.45% of organic farms participating in this survey. Organic farming residues are used on overwhelming organic farms, and a little organic waste is unusable (discharged or burned) on 37.1% of organic farms (Fig. 14).

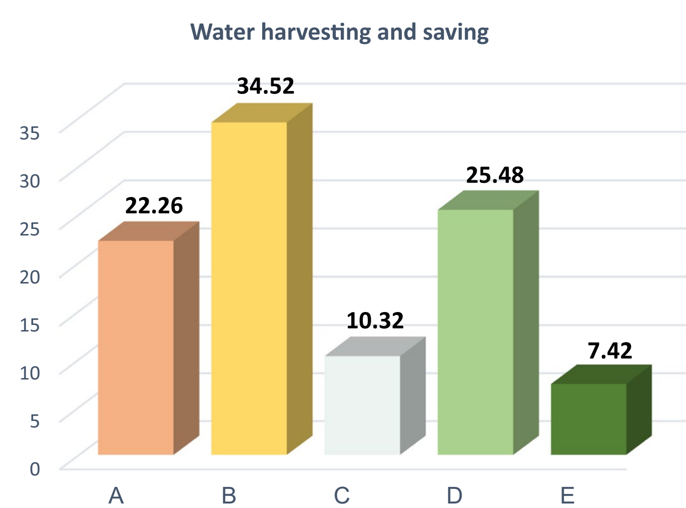


A	No recycling of organic farming residues
B	A small part of organic farming residues is used. Organic waste was discharged or burnt
C	More than 50% of organic farming residues are used: crop, vegetable, spices, and fruit leftovers are used as animal feed, manure of compost, or fertilizer
D	Most of the organic farming residues are used. There is a little discharged or burned waste
E	All organic farming residues are used. There is no waste on the farm

Fig. 14 Biomass and nutrients recycling

4.6.2 Harvesting and saving water system

Collecting and storing the rainy precipitation towards stream channels constituted an important strategy for harvesting and saving water. Organic agricultural production still depends on rainfall, and the equipment or technical requirements to harvest and save water would be important in organic farming. Without any technical means to protect the soil or harvest water, a large part of the rainfall evaporates into the atmosphere from the soil surface, and a little is infiltrated into the soil for agricultural production. However, water harvesting and saving reduced the vulnerability of organic farming due to the variability of rainfall and developed irrigation systems. The findings show that 22.26% of organic farmers responding don't have any equipment or techniques for water harvesting or saving, while 34.52% have one type of equipment, such as drip irrigation or tanks, to harvest and save water (Fig. 15).



A	No equipment or techniques to harvest and save water
B	One equipment (drip irrigation or tank) to harvest or save water
C	One equipment (drip irrigation or tank) to harvest or save water + techniques to reduce water use
D	One equipment (drip irrigation or tank) to harvest and save water, and some techniques to optimize water use
E	Several equipment to harvest and save water + some techniques to optimize water use

Fig. 15 Harvesting and saving water system

4.6.3 Seeds and animal genetic autonomy

Seeds and animal genetics are important components of diversity and variability in agricultural production. In organic farming, the seeds and animal genetics determine the resistance of organic production to climate change, pests, and diseases. Then, the seeds and animal management are based on the preservation of local varieties of seeds and animal genetics. The findings highlighted that the seeds used for organic production and animals genetic for organic breeding are self-produced or obtained from exchanging with neighbors' farmers for 51.61% of the organic farmer respondents. However, some specific organic seeds and animal genetics were provided by external (Fig. 16).

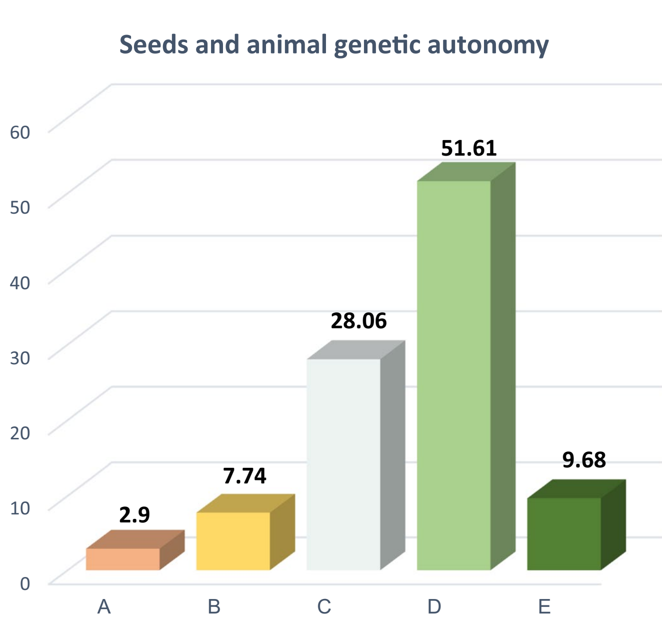
4.7 Resilience

4.7.1 Income stability and recovery capacity from climate shocks or perturbations

Income stability refers to the organic farming production level. The stability of income indicated a constant level of profit margins, which guarantee a favorable environment for capital investment in organic agricultural production. Organic farming can be sustainable as soon as income is stable, reducing vulnerability through the capacity to recover from perturbations. The stability through production and income proves the organic resilience to face venerability and the capacity to adapt to ecosystem changes. According to the findings, for 47.74% of organic farmers, income declined and production varied from year to year with constant organic inputs. These incomes and productions are mostly recovered after shocks or perturbations (Fig. 17).

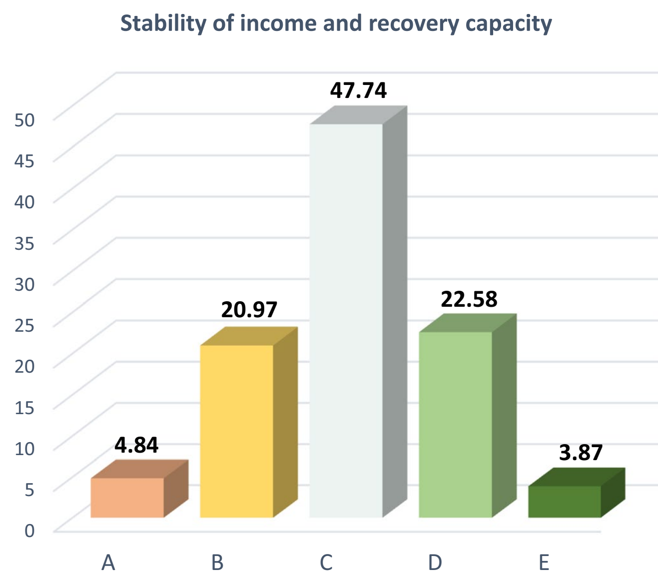
4.7.2 Resilience and adaptability to climate variability

In response to increasing environmental threats such as storms, droughts, and floods, organic farming practices are a palliative approach to mitigate the impacts. This organic farming practice can reflect resilience in the environment through its practices to alleviate the effects of climate variability. The finding revealed that organic farming is still subjected to climatic shocks, but the organic farmers (40.65%) have built systems that have a good capacity to overcome these difficulties of climate (Fig. 18).



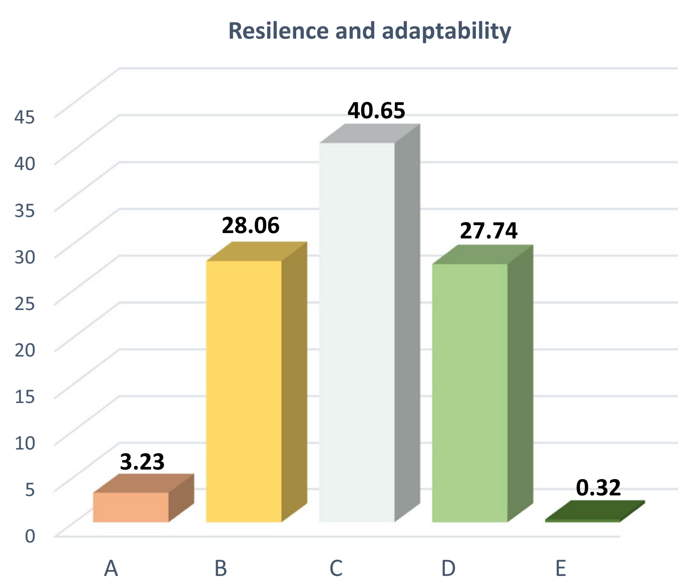
A	All organic seeds and animal genetic breeding were provided by external sources
B	80% of organic seeds and animal genetic breeding were provided by external sources
C	About 50% of the organic seeds and animal genetic breeding is obtained by exchanging with neighboring farmers.
D	External sources contribute a little to organic seeds and animal genetic breeding; the majority is self-produced or obtained by exchanging with neighboring farmers.
E	All of the organic seeds and animal genetic breeding were self-produced or obtained by exchanging with neighboring farmers.

Fig. 16 Seeds and animal genetic autonomy



A	Production is decreasing, resulting in income failure with the constant level of organic inputs used. Any capacity to recover after shocks or perturbations.
B	Production is decreasing with constant input, which entails reducing income. Climate shocks or perturbations can be difficult to recover from.
C	Organic income is declined and production is variable from year to year with constant inputs with good capacity to recovery
D	Production varies a little from year to year (with constant inputs) with income stable with good capacity to recovery
E	Over time income and production are increasing with the capacity to recover after shocks or perturbations quickly

Fig. 17 Income stability and recovery capacity from climate shocks or perturbations



A	Organic farming is highly subjected to climatic shocks without adaptability systems
B	Organic farming is subjected to climatic shocks but has the system to alleviate climate variability effects
C	Organic farming is exposed to climatic variability shocks but has a good system to overcome the difficulties
D	Organic farming is exposed to climatic variability shocks but has a strong system to overcome the difficulties
E	Organic farming has a strong natural capital base, climatic shocks are rare; and it has a strong system to overcome all difficulties of climate

Fig. 18 Resilience and adaptability to climate variability

4.8 Relations between agroecology principles (diversity, synergies, recycling, resilience)

The scoring is used for the assessment of agroecology principles implemented by organic farmers in Central Uganda. Each indicator for agroecology principles was scored from 0 to 4. The findings show that the indicator the biomass and nutrient recycling (2.82 ± 0.951) has a high score following the seeds and animal genetic autonomy (2.57 ± 0.877), and diversity crop (2.49 ± 0.819) (Table 5). The diversity of activities and services (1.12 ± 0.78) and diversity of animal genetics (1.55 ± 0.777) are still the challenges for organic farmers in Central Uganda. The value of the Pearson correlation coefficient r indicates the relationship between diversity, synergies, recycling, and resilience (Table 3). It

Table 5 Descriptive analysis

Variable	N	Mean	Std. Deviation	Min	Max
Diversity crops (Dcrop)	310	2.49	0.819	0	4
Diversity animals spices (Danim)	310	1.55	0.777	0	4
Diversity activities and services (Dact)	310	1.12	0.78	0	4
Crop and livestock integration (Scliv)	310	1.77	0.842	0	4
Soil protection system by plants (Spl)	310	2.15	0.679	0	4
Agroforestry and silvopastoralism practices (Stre)	310	1.7	0.67	0	4
Recycling of biomass and nutrients (Rbio)	310	2.82	0.951	0	4
Harvesting and saving water system (Rwate)	310	1.61	1.282	0	4
Seeds and animal genetic autonomy (Rseed)	310	2.57	0.877	0	4
Income stability and recovery capacity from climate shocks or perturbations (Resinc)	310	2	0.887	0	4
Resilience and adaptability to climate variability (Resen)	310	1.94	0.836	0	4

highlights that there is a medium significant positive correlation between diversity animal genetics and crop and livestock integration ($r = +0.674$, $p < 0.01$), between the harvesting and saving water systems and resilience and adaptability to climate variability ($r = +0.546$, $p < 0.01$), and between diversity crops and diversity activities and services ($r = +0.523$, $p < 0.01$) (Table 4). There is a low significant negative correlation between harvesting and saving water systems, and biomass and nutrient recycling ($r = -0.24$, $p < 0.01$) (Table 6).

5 Discussion

The study focuses on organic farming analysis through an agroecological approach that emphasizes four agroecology principles: diversity, synergies, recycling, and resilience. These agroecological principles rely directly on organic farming, according to the conceptual framework designed by Dagoudo et al. [12]. The majority (52.9%) have at least three crops that have been produced in the local climate for a long time. The organic farming system encompasses the small-scale farmer who produces grains, fruits, vegetables, fodder, and animal products in the same field or garden and out-produces the yield per unit of single crops such as corn grown alone on large-scale farms [1]. Crop diversity is one of the agroecological principles most implemented by organic farmers, according to the agroecology assessment scale. The diversity of cropping systems in organic farming encompasses different varieties of crops produced in various spatial settings, protects traditional agroecosystems, and contributes to a sporadic reduction of vulnerability to shocks from climate variability [31]. The results revealed that the majority (58.71%) of organic farming has crop-livestock medium

Table 6 Correlation test

	Dcrop	Danim	Dact	Scliv	Spl	Stre	Rbio	Rwate	Rseed	Resinc	Resen
Dcrop	1										
Danim	0.442**	1									
Dact	0.523**	0.487**	1								
Scliv	0.382**	0.674**	0.465**	1							
Spl	0.313**	0.247**	0.323**	0.370**	1						
Stre	0.445**	0.425**	0.525**	0.491**	0.465**	1					
Rbio	0.204**	0.242**	0.1108	0.304**	0.200**	0.125*	1				
Rwate	−0.054	0.0286	0.178**	0.0693	0.228**	0.175**	−0.24**	1			
Rseed	0.221**	0.144*	0.172**	0.251**	0.283**	0.247**	0.433**	0.1004	1		
Resinc	0.122*	0.0870	0.216**	0.164**	0.270**	0.244**	0.018	0.329**	0.165**	1	
Resen	−0.0549	0.0369	0.115*	0.136*	0.267**	0.164**	0.047	0.546**	0.211**	0.327**	1

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed) integration, which means animal feed is mostly self-produced and grazing, and their manure is used for compost and fertilizer. For [32], the integration of crop-livestock systems is beneficial for weed, pest, and disease control, and protects the ecological environment. This includes some challenges such as the availability of resources for pasture-cropping, grazing, and groundcover maintenance in high rainfall zones and the management of persistent weeds and pests. The findings of the research highlight that the seeds and animal genetics for organic farming are in the majority (51.61%) self-produced and neighbor farms exchanged, and some specific seeds are purchased at local markets. Thus, local genetic diversity refers to multiple-cropping or poly-culture systems that conserve soil organic matter for resilience against extreme climate events [33]. In agriculture, plant and animal diversity management constitutes the potential sources of systems to alleviate the effects of climate variability as well as provide nutritious and healthy foods [34]. However, the result of the study revealed that the environment for organic farming is still exposed to climatic shocks or perturbations for the majority of organic farmers (40.65%). In Central Uganda, where organic farmers participate in this research, 50% of the cultivation soil is covered with organic residues on the majority (61.61%) organic farms. The crops on the farm are rotated and intercropped. For some authors, crop rotations are the principal management practices that organic farmers overwhelmingly use as conversion strategies for influencing forage production, building fertility, and controlling some weeds, pests, and diseases [35]. In 26.45% of farms, more than 50% of organic farming residues are recycled, which encompass crop, vegetable, spice, and fruit residues, and are usually used as animal feed, manure, compost, or fertilizer. A little organic waste is discharged or burned. The soil covered by organic farming residues recycled shows important strategies implemented by organic farmers to conserve the wetness of the soil and reduce erosion. In Canada, the experience revealed that 15% of the corn residue cover fraction can reduce soil erosion by as much as 75% [36]. However, minimizing crop failure through increased use of drought-tolerant local seeds and animal genetic varieties, water harvesting and saving, rotation and intercropping, agroforestry, and a series of other traditional farming system techniques has the potential to help farmers cope with and even prepare for climate variability [37]. In organic farming, 22.26% of respondents don't have any equipment or techniques to harvest and save water, and 34.52% have one type of equipment, such as drip irrigation or tanks, for harvesting and saving water. Therefore, according to some authors, integrated water management provides large co-benefits for climate variability adaptation [38] by improving the resilience of food crop production systems [39]. The findings highlight that 47.74% of organic farmers' income declined with constant inputs for production, and they are able to recover after climate shocks or perturbations. Agroecological practices have the potential for resilience to protect from climate shocks or perturbations and spread farmer risk of pests and diseases [40]. The significant correlation between harvesting and saving water systems and resilience and adaptability to climate variability explains that water management is the key resource to driving organic farming to agroecological farming. The challenge is that organic farming in Central Uganda still depends mostly on rainfall, with few equipment and techniques to harvest and save water. Water management affects directly agricultural productivity [9, 41], and land practices [42], and has the potential to mitigate up to 60% of greenhouse gas emissions [43–48]. Therefore, the significant positive correlation between diversity in animal genetics and crop and livestock integration proved that livestock management is important for manure provision. Livestock management through animal genetic diversity increased organic farming productivity, agroecosystem productivity, and reduced emissions from enteric fermentation [49–52].

6 Conclusion and recommendations

Organic farming in Central Uganda is a holistic management system that encompasses the production of crops, vegetables, fruits, spices, and no timber products (herbs, fruits) production. In organic farming, different agroecological practices were registered, such as crop diversity, intercropping, agroforestry, silvopastoralism, Soil protection systems by plants, harvesting, and saving water. However, the findings highlighted that in Uganda Central, organic farmers have a good level of crop diversity through seeds and animals' genetic variety. However organic farming is vulnerable because of the low level of diversity in productive activities and services. The results revealed that organic farming has an important number of trees and perennials that participate in the synergies through mostly animal feed and grazing and provide manure for compost and fertilizer (medium integration). Mostly organic farming residues are used and a little organic waste is unusable (discharged or burned). As a strategy to prevent and alleviate the effects of climate variability, organic farmers recycle water resources towards the possession of equipment and techniques such as drip irrigation or tanks for harvesting and saving water. The majority of organic farming is exposed to climatic variability shocks or perturbations and income declined year after year with variable production. Despite agroecology practices observed in organic farming, farmers must still make efforts in a diversity of animal species and activities, integration of crops and livestock, agroforestry, and systems for harvesting and saving water to reach the medium for agroecology farming. Based on the findings, some recommendations are proposed to move toward agroecological farming.

- Organic farmers should invest in animals' diversity for organic manure availability for crop production;
- Organic farmers should invest more in agroforestry, silvopastoralism because they contribute sequestration of carbon in vegetation and soils;
- The government and the other partners should reinforce the organic farmers' technical for water harvesting and saving and should promote genetic crops and animal diversity.

Acknowledgements We would like to thank the Intra-Africa Academic mobility Program scholarship under the Regional Academic Exchange for Enhanced Skills in Fragile Ecosystems Management in Africa (REFORM) for supporting my PhD study, AFIRD and St. Jude Family Project staff, and organic farmers participating in the survey.

Author contributions Conceptualization: B. A. D.; Methodology: B. A. D.; Formal analysis and investigation: B. A. D. and K. D.; Writing—original draft preparation B. A. D.; Writing—review and editing: H. N. and I. M. M.; Supervision: C. S. and J. S.; coordinated project administration: K. N; All authors have read and agreed to the published version of the manuscript.

Funding The research did not receive any funding.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent for publication Informed consent was obtained from all subjects and their legal guardians.

Competing interests The authors declare that they have no conflict of interest.

References

1. Altieri MA. Agroecology, small farms, and food sovereignty. Mon Rev. 2009;61:102–13.
2. Denevan WM. 2 Prehistoric agricultural methods as models for sustainability. In: Advances in plant pathology. Elsevier; 1995. p. 21–43. https://doi.org/10.1016/S0736-4539(06)80004-8.
3. Kenmore PE, Stannard C, Thompson PB. The ethics of sustainable agricultural intensification. Food & Agriculture Org; 2004.
4. Rosset P. Food is different: why we must get the WTO out of agriculture. Zed Books; 2006.
5. Zulfiqar F, Thapa GB. Is 'Better cotton' better than conventional cotton in terms of input use efficiency and financial performance? Land Use Policy. 2016;52:136–43.
6. Zulfiqar F, Ullah R, Abid M, Hussain A. Cotton production under risk: a simultaneous adoption of risk coping tools. Nat Hazards. 2016;84:959–74.
7. Rempelos L, Baranski M, Wang J, Adams TN, Adebusuyi K, Beckman JJ, et al. Integrated soil and crop management in organic agriculture: a logical framework to ensure food quality and human health? Agronomy. 2021;11:2494.
8. Hansen AL. The organic farming manual: a comprehensive guide to starting and running a certified organic farm. Storey Publishing, LLC; 2010.
9. Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci. 2011;108:20260–4.
10. Tittonell P, Giller KE. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res. 2013;143:76–90.
11. IFOAM. organic-world.net—the world of organic agriculture 2022—Download PDF; 2022. https://www.organic-world.net/yearbook/yearbook-2022/yearbook-2022-download-pdf.html
12. Dagoudo BA, Ssekyewa C, Tovignan SD, Ssekandi J, Nina PM. Agroecological business model: a pillar stone for women's entrepreneurship in agroecology and sustainable food systems. Int J Curr Sci Res Rev. 2023;6:296–304.
13. Wezel A, Silva E. Agroecology and agroecological cropping practices. Agroecological practices for sustainable agriculture: principles, applications, and making the transition. World Scientific; 2017. p. 19–51.

14. FAO. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. FAO Rome, Italy; 2019. http://www.fao.org/3/i9021en/I9021EN.pdf
15. FAO. FAO's Work on Agroecology: A Pathway to Achieving the SDGs. FAO Rome; 2018. Available from: http://www.fao.org/3/i9021en/i9021en.pdf
16. Petersen P, Arbenz M. Scaling up agroecology to achieve the SDGs: a political matter. Farm Matters. 2018;34:6–9.
17. IFOAM. Principles of organic agriculture; 2008. https://www.ifoam.bio/principles-organic-agriculture-brochure
18. Francis C, Lieblein G, Gliessman S, Breland TA, Creamer N, Harwood R, et al. Agroecology: the ecology of food systems. J Sustain Agric. 2003;22:99–118. https://doi.org/10.1300/J064v22n03_10.
19. Gliessman S. Transforming food systems with agroecology. Agroecol Sustain Food Syst. 2016;40:187–9. https://doi.org/10.1080/21683565.2015.1130765.
20. Altieri MA. Agroecology: the science of sustainable agriculture. 2nd ed. CRC Press; 1995.
21. Wezel A, Casagrande M, Celette F, Vian J-F, Ferrer A, Peigné J. Agroecological practices for sustainable agriculture. A review. Agron Sustain Dev. 2014;34:1–20.
22. Dumont AM, Vanloqueren G, Stassart PM, Baret PV. Clarifying the socioeconomic dimensions of agroecology: between principles and practices. Agroecol Sustain Food Syst. 2016;40:24–47. https://doi.org/10.1080/21683565.2015.1089967.
23. Anderson CR, Bruil J, Chappell MJ, Kiss C, Pimbert MP. From transition to domains of transformation: getting to sustainable and just food systems through agroecology. Sustainability. 2019;11:5272.
24. UBOS. Uganda Annual Agricultural Survey 2018. 2020. https://www.ubos.org/explore-statistics/20/. Accessed 8 Feb 2023.
25. Majaliwa JGM, Tenywa MM, Bamanya D, Majugu W, Isabirye P, Nandozi C, et al. Characterization of historical seasonal and annual rainfall and temperature trends in selected climatological homogenous rainfall zones of Uganda. Glob J Sci Res. 2015;15:21–40.
26. Mottet A, Bicksler A, Lucantoni D, De Rosa F, Scherf B, Scopel E, et al. Assessing transitions to sustainable agricultural and food systems: a tool for agroecology performance evaluation (TAPE). Front Sustain Food Syst. 2020;4: 579154.
27. Halvey MJ, Keane MT. An assessment of tag presentation techniques. In: Proceedings of the 16th international conference on World Wide Web; 2007. p. 1313–4.
28. Lohmann S, Ziegler J, Tetzlaff L. Comparison of tag cloud layouts: Task-related performance and visual exploration. In: Human-computer interaction–INTERACT 2009: 12th IFIP TC 13 international conference, Uppsala, Sweden, August 24-28, 2009, proceedings, Part I 12. Springer; 2009. p. 392–404.
29. Rivadeneira AW, Gruen DM, Muller MJ, Millen DR. Getting our head in the clouds: toward evaluation studies of tagclouds. In: Proceedings of the SIGCHI conference on Human factors in computing systems; 2007. p. 995–8.
30. Bateman S, Gutwin C, Nacenta M. Seeing things in the clouds: the effect of visual features on tag cloud selections. In: Proceedings of the nineteenth ACM conference on Hypertext and hypermedia; 2008. p. 193–202.
31. Zhu X, Clements R, Quezada A, Torres J, Haggar J. Technologies for climate change adaptation. Agriculture sector; 2011. http://www.risoe.dtu.dk/rispubl/NEI/NEI-DK-5548.pdf. OSTI as DE01026421
32. Nie Z, McLean T, Clough A, Tocker J, Christy B, Harris R, et al. Benefits, challenges and opportunities of integrated crop-livestock systems and their potential application in the high rainfall zone of southern Australia: a review. Agr Ecosyst Environ. 2016;235:17–31.
33. Altieri MA, Koohafkan P. Enduring farms: climate change, smallholders and traditional farming communities. Third World Network (TWN) Penang; 2008.
34. Wezel A, Herren BG, Kerr RB, Barrios E, Gonçalves ALR, Sinclair F. Agroecological principles and elements and their implications for transitioning to sustainable food systems A review. Agron Sustain Dev. 2020;40:1–13.
35. Nicholls CI, Altieri MA, Vazquez L. Agroecological principles for the conversion of farming systems. In: Agroecological practices for sustainable agriculture: principles, applications, and making the transition; 2017. p. 1–18.
36. Ketcheson JW, Stonehouse DP. Conservation tillage in Ontario. J Soil Water Conserv. 1983;38:253–4.
37. Browder JO. Fragile lands in Latin America: strategies for sustainable development. Boulder: US. Westview Press; 1989.
38. Dillon P, Arshad M. Managed aquifer recharge in integrated water resource management. In: Integrated groundwater management: CONCEPTS, approaches and challenges; 2016. p. 435–52. https://doi.org/10.1007/978-3-319-23576-9_17
39. Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, et al. Chapter 7: Food Security and Food Production Systems. In: Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Chan. Cambridge University Press; 2014. p. 485–533.
40. Niles MT, Ahuja R, Barker T, Esquivel J, Gutterman S, Heller MC, et al. Climate change mitigation beyond agriculture: a review of food system opportunities and implications. Renew Agric Food Syst. 2018;33:297–308.
41. Godfray HCJ, Garnett T. Food security and sustainable intensification. Philos Trans R Soc B Biol Sci. 2014;369:20120273. https://doi.org/10.1098/rstb.2012.0273.
42. Pierzynski G, Brajendra CL, Vargas R. Threats to soils: global trends and perspectives. global land outlook working paper 28. Secretariat of the United Nations …; 2017.
43. Beach RH, Creason J, Ohrel SB, Ragnauth S, Ogle S, Li C, et al. Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030. J Integr Environ Sci. 2015;12:87–105.
44. Dickie IA, Bennett BM, Burrows LE, Nuñez MA, Peltzer DA, Porté A, et al. Conflicting values: ecosystem services and invasive tree management. Biol Invasions. 2014;16:705–19. https://doi.org/10.1007/s10530-013-0609-6.
45. Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proc Natl Acad Sci. 2017;114:11645–50. https://doi.org/10.1073/pnas.1710465114.
46. Hawken P. Drawdown: The most comprehensive plan ever proposed to reverse global warming. Penguin; 2017.
47. Hussain S, Peng S, Fahad S, Khaliq A, Huang J, Cui K, et al. Rice management interventions to mitigate greenhouse gas emissions: a review. Environ Sci Pollut Res. 2015;22:3342–60.
48. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. Nature. 2016;532:49–57.

49. Archer SR, Davies KW, Fulbright TE, Mcdaniel KC, Wilcox BP, Predick KI. Brush management as a rangeland conservation strategy: A critical evaluation. In: Briske DD, editor. Conservation benefits of rangeland practices: Assessment, recommendations, and knowledge gaps. Washington, DC; 2011. p. 105–70.
50. Herrero M, Henderson B, Havlík P, Thornton PK, Conant RT, Smith P, et al. Greenhouse gas mitigation potentials in the livestock sector. Nature Clim Change. 2016;6:452–61.
51. Miao L, Moore JC, Zeng F, Lei J, Ding J, He B, et al. Footprint of research in desertification management in China. Land Degrad Dev. 2015;26:450–7. https://doi.org/10.1002/ldr.2399.
52. Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA. Climate change and livestock: Impacts, adaptation, and mitigation. Clim Risk Manag. 2017;16:145–63.