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TITLE:

COMBINING AGROECOLOGICAL INTENSIFICATION OPTIONS THROUGH FARMERS' NETWORKS TO OPTIMISE PRODUCTIVITY IN THE CLIMATE CHANGE CONTEXT OF NIGER

A thesis, in the Rural Polytechnic Institute of Training and Applied Research (IPR/IFRA) in partnership with the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), submitted in partial fulfilment of the requirements for the Doctor of Philosophy in Climate Change and Agriculture of the University of Sciences, Techniques and Technologies of Bamako (USTTB)

Presented and defended on: **19/05/2023**

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COMBINING AGROECOLOGICAL INTENSIFICATION OPTIONS THROUGH FARMERS' NETWORKS TO OPTIMISE PRODUCTIVITY IN THE CLIMATE CHANGE CONTEXT OF NIGER

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- **Manuscript 3 :** "Ongoing"

Performance of cowpea genotypes selected through participatory varietal selection and participatory breeding under different local contexts of the smallholder farmers in Niger

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- Participation to the kick-off meeting of the EQUITAE project led by the farmers' federation Mooriben from 12th to 16th March 2023. The integrative trial design will also be used in the project work.

DEDICATION

This modest piece of work is dedicated to the **smallholder farmers** of **Niger Republic** who always strive to improve their livelihoods despite the adverse climate change impacts.

"Transdisciplinary Research combined with Participatory Research can push family farming forward, not an individual PhD." (This thesis)

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LIST OF ACRONYMS AND ABBREVIATIONS

AEI: Agroecological Intensification

ANADIA : AdaptatioN Au changement climatique, prévention des catastrophes et Développement agrIcole pour la sécurité Alimentaire

CCRP: Collaborative Crop Research Program

CVD : Cowpea Varietal Diversity

CIRAD : Centre International pour la Recherche Agronomique et le Développement

CS : CowpeaSquare

CSs : Cropping Systems

DAP: Diamonium Phosphate

DMN : Direction de la Météorologie Nationale du Niger

DPI : Dual-Purpose Index

FAO: Food and Agriculture Organization

FAMD: Factor Analysis of Mixed Data

FRNs: Farmer Research Networks

ICRISAT: International Crop Research Institute for the Semi-Arid Tropics

IMAAN : Ingénierie de Management en Agronomie et Agro-alimentaire

INRAN : Institut National pour la Recherche Agronomique du Niger

INS : Institut Nationale de la Statistique

IPCC: Intergovernmental Panel on Climate Change

IPR/IFRA : Institut Polytechnique Rural et la Formation et Recherche Appliquée

IRD : Institut de Recherche pour le Développement

IVM : Indice de vote Multicritère

MF: Main field

NPK: Nitrogen Phosphorus and Potassium

RCBD: Randomized Complete Block Design

SFM: Soil Fertility Management

SSA: Sub-Saharan Africa

UDDM : Université Dan Dicko Dankoulodo de Maradi

USTTB : Université des Sciences, des Techniques et des Technologies de Bamako

WF: Female field

WASCAL: West African Science Service Center on Climate Change and Adapted Land Use
CC&A: Climate Change and Agriculture.

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ABSTRACT

Family farms are crucial for food security and nutrition in West Africa. Yet multiple technologies have been promoted and disseminated as a means to meet food security. However, the diversity of management practices in the family farming including intercropping, pest and soil fertility management, makes it difficult to find standard options that will fit the need and the possibilities of smallholder farmers. This PhD work aimed to explore innovative combined options for agroecological intensification (AEI) in the Sahelian zone of Niger. A baseline survey was used in exploring potential AEI options. An integrative pilot trial design was co-built through four main steps for identifying the most promising combined AEI options in the local contexts. And decentralized trials were also used to test a set of dual-purpose cowpea varieties across the selected fifteen study locations. Results showed that family farms were mainly characterized by the presence of the main field (98%) led by the head and the presence of female field(s) (78%) led by the women and they highly rely on rain fed agriculture. The key drivers impeding crop productivity was the significant decrease in soil fertility (70%). About 12 potential AEI were identified including the use of organic manure and intercropping millet-cowpea. With respect to the integrative trial design, findings showed that farmers tended to opt for the use of decomposed organic manure combined with the intercropping options and any of the two dual-purpose cowpea varieties compared to the remaining combined options. The assessment of the performance of the cowpea genotypes/varieties revealed that the selected cowpea genotypes significantly ($p \leq 0.05$) yielded better than the control varieties concerning pod and haulm yields in ten study locations out of fifteen. In the cluster of the selected varieties (classical), the CS012 variety had the highest median pod yield of 380.5 kg. ha^{-1} while the CS001 recorded the largest median haulm yield of 1,078 kg. ha^{-1} in Djinde Mario. Whereas in the cluster of the selected genotypes (multiline), the CWS-RIL-31-46 gave the highest pod and haulm yields of 284.5 kg. ha^{-1} and 398.5 kg. ha^{-1} respectively, compared to the local varieties. This study revealed that developing technologies/options and approaches to increase crop productivity and farmers' livelihoods without considering the diversified local contexts as well as farmers' needs and their full participation at the early stage of the project are indeed less useful. Integrative trial design fills the gap of the lack of methodology integrating the experiences of researchers and farmers and it represent pathways to increase crop productivity and smallholder farmers' livelihoods.

Key words: Agroecological intensification, options by context, integrative trial design, family farms, intercropping, Niger

RESUME

Les exploitations familiales sont déterminantes pour la sécurité alimentaire et la nutrition en Afrique de l'Ouest. Pourtant, de multiples technologies ont été promues et diffusées comme moyen d'assurer la sécurité alimentaire. Cependant, la diversité des pratiques de gestion dans les exploitations familiales, y compris les associations culturales, la gestion des ravageurs et de la fertilité des sols, fait qu'il est difficile de trouver des options standard qui répondront aux besoins et aux possibilités des petits exploitants agricoles. Ce travail de doctorat visait à explorer des options combinées innovantes pour l'intensification agroécologique (IAE) dans la zone sahélienne du Niger. Une étude de base a été utilisée pour explorer les options potentielles d'IAE. Un modèle d'essai pilote intégratif a été coconstruit à travers quatre étapes principales pour identifier les options combinées d'IAE les plus prometteuses dans les contextes locaux. Des essais décentralisés ont également été conduits pour tester une gamme des variétés de niébé double usage dans les quinze sites d'étude sélectionnés. Les résultats ont montré que les exploitations familiales étaient principalement caractérisées par la présence d'un champ principal (98%) dirigé par le chef et d'un ou plusieurs champs féminins (78%) dirigés par les femmes, et qu'elles dépendaient fortement de l'agriculture pluviale. Le principal obstacle à la productivité agricole est la baisse significative de la fertilité des sols (70 %). Une douzaine d'options d'IAE potentielles ont été identifiées, notamment l'utilisation de fumier organique et l'association culturale de mil-niébé. En ce qui concerne la co-conception de l'essai intégratif, les résultats ont montré que les paysans avaient tendance à opter pour l'utilisation de fumier organique décomposé combiné aux options de l'association culturale et à l'une des deux variétés de niébé à double usage, par rapport aux autres options combinées. L'évaluation de la performance des génotypes/variétés de niébé a révélé que les génotypes de niébé sélectionnés avaient un rendement significativement ($p \leq 0,05$) supérieur à celui des variétés utilisées comme témoin en ce qui concerne les rendements en gousses et en fanes dans dix sites d'étude sur quinze. Dans le groupe des variétés sélectionnées (classiques), la variété CS012 a eu le rendement moyen en gousses le plus élevé de 380,5 kg.ha^{-1} tandis que la variété CS001 a enregistré le plus grand rendement en fanes de 1078 kg.ha^{-1} à Djinde Mario. Alors que dans la grappe du génotype sélectionné (multiligne), le CWS-RIL-31-46 a donné les rendements en gousses et en fanes les plus élevés de 284,5 kg.ha^{-1} et 398,5 kg.ha^{-1} respectivement, par rapport aux variétés locales. Cette étude a révélé que le développement de technologies/options et d'approches visant à accroître la productivité des cultures et les moyens de subsistance des agriculteurs sans tenir compte des contextes locaux diversifiés ainsi que des besoins des paysans et de leur pleine participation dès le début du projet est en effet moins utile. La conception d'essais intégratifs comble le manque de l'approche méthodologique intégrant les expériences des chercheurs et des agriculteurs et représente des voies permettant d'accroître la productivité agricole et les moyens de subsistance des petits exploitants.

Mots clés : Intensification agroécologique, option par contexte, essai intégratif, exploitation familiale, association culturale, Niger

CHAPTER ONE: INTRODUCTION

1.1.Problem and justification

Adaptation to climate change is of vital importance to the smallholder farmers of Niger, who are highly exposed to various types of risks (climatic, economic, health and even security). Adaptation to climate change in the Agriculture, Forestry and Other Land Uses (AFOLU) sector is thus a major challenge for the economic development of Niger. However, agriculture, livestock, forestry, logging and fishing generate 38.4% of the country's Gross Domestic Product (GDP) (INS, 2019), and 80% of jobs, for an arable and cultivated area estimated at 13% of the total national territory in 2017. Food security remains a critical concern in West Africa with about 70% of the rural population who are mostly smallholder farmers being constantly food insecure in this context of changing climate (FEWSNET, 2019). For instance, Niger has a population growth rate of 3.7%, the highest in the world (MPL, 2020), indicating that the need for sustainable and resilient dietary crops is expected to increase in Niger. This calls for the exploration of new ways of sustainable intensification of smallholder farming systems to support adaptive capacities of the farmers to meet the growing demand for food availability. However, crop productivity in smallholder farming systems in the Sahelian zone of Niger continues to be impeded by poor and declining soil fertility, mostly phosphorus and nitrogen availability (Bationo et al., 2007; Ibrahim et al., 2016). This is coupled with climate stresses (particularly irregular rainfall) and weak financial capacity of smallholder farm households to purchase adequate food needs to supplement their food production. On the other hand, one of the main bottlenecks of farming system in sub-Saharan Africa is that conventional agricultural research tends to be top-down (Rebecca Nelson, 2016) and isolated from smallholder farmers and their local ecological, economic, and social realities. As a result, farmers often find the products of the research from seed varieties and tools to policy recommendations inaccessible, irrelevant, or non-functional (Coe et al., 2019). As a consequence, these challenges continue strengthening food insecurity in West Africa despite significant investment in agricultural production and hence sustainable intensification of land offers an avenue for smallholder farmers to increase crop productivity (Rebecca Nelson, 2016; P. Taylor et al., 2011).

This concept suggests the aims of reducing the environmental costs of agriculture in the industrialized world and increasing production in poor countries with a minimum of damage to the environment (Balmford et al. 2012; Rebecca & Coe, 2015). However, the concept does not imply much about how these aims will be achieved or assessed, and perhaps this ambiguity is the basis of its popularity. Further, agroecological intensification (AEI) practices seems to be more adapted to local contexts as the concept implies a concern for sustainability, but it suggests a further commitment to intensification strategies that emphasize the use of processes of biology and ecology to attain this. As defined by Wezel et al. (2015), "AEI is a way of improving the performance of agriculture while minimizing environmental impacts and reducing dependency on external inputs through integration of ecological principles into farm- and system management." Thus, depending on the context, improved performance may mean any or all of the following: improved efficiency, increased productivity, enhanced use of local resources, better diets, improved livelihoods, and increased equity with associated improvement in resilience and ecosystem services provision from farm to landscapes (CCRP, 2021). AEI practices positively respond to the need of farming systems in sub–Saharan Africa especially in Sahel region where the system is dynamic and complex (Falconnier *et al.*, 2016; Sinclair & Coe, 2019; van Wijk *et al.*, 2009). Hence, supporting smallholder farmers based on agroecological principles and practices are necessary. Practices like biological control of insects, a balanced and more efficient use of fertilizers (fertilizer or wood ash micro-dosing), farmer-selected varieties (for pearl millet, sorghum, cowpea, groundnut, etc.), intercropping, crop rotation, seedballs technology, use of "*Oga*" (localized application of fermented human urine as nitrogen fertilizer), agroforestry and livestock integration are mentioned as likely efficient AEI strategies in Niger (CCRP, 2021). Nevertheless, the question is that can these agroecological intensification option/practices meet the need of the smallholder farmers, increase crop productivity and enable farmers to better adapt to the current climate change impacts? It presumably difficult to answer because AEI options can be influenced by the biophysical (e.g., climate, length of growing season, soil type and fertility, farm size) and socio-economic (finances, input and output markets) properties of smallholder farms. There exists a large variability among agroecological zones and farms within the different zones of the Sahel in terms of the above-mentioned properties. Moreover, human and social factors differ between locations. Therefore, evaluation of the AEI options needs to take in consideration such differences in resources and their influence on the suitability and productivity of each option.

Yet, the assessment of both spatial and temporal AEI options like cowpea and pearl millet intercropping to offer opportunities for smallholder farms in the Sahel have largely been confined to on-stations experiments rather than on-farm trials. Most of these studies (Sanou et al., 2016; Garba *et al.*, 2018 ; Suzuki *et al.*, 2017; Ibrahim *et al.*, 2015; Siebou et al., 2019;

Mahaman Sanoussi, 2018) do not consider the diversity of soil fertility conditions in farmers' fields and the relative differences in other biophysical properties between farms in contrasting locations. Moreover, previous studies (Kermah, 2020; Ronner, 2018 ; Falconnier, 2016 ; Samaké, 2003 ; Mariana, 2008) ; Rusinamhodzi, 2013) have focused mainly on studying the grain legumes-cereals intercropping and legume-cereal rotations as the most adapted options for agroecological intensification using on-farm trials but with limited experimental locations. Options for agroecological intensification in the local contexts of smallholder farmers especially in Sahel requires considerable on-farm trials and participation of large number of farmers.

In this regard, the use of participatory research approach is necessary to deal with cropping constraints in the diversified local contexts rather than conventional agronomic methods. This approach helps identifying agroecological intensification options adapted to smallholder farmers. For instance, the farmers' trial networks with large samples of farms (Decentralized trials) offer powerful framework for making robust assessment of crop options in a design copping with a diversity of local management options. The approach has revealed a strong will of farmers to test different technologies in their fields after a first trial on 200 farmers (Saidou & Sani Issa, unpublished). However, studies that used the combination of options for agroecological intensification in which was employed an approach combining on-farm testing and participatory modelling of the combined options are scanty in Niger.

Knowledge is needed on how to make the diversity of local options of crop management (including intercropping, and soil fertility management) feasible to find standard options that will enable smallholder farmers to increase the climatic resilience of their farms.

Additionally, insights are needed on the potential impacts of the innovative combination of options for agroecological intensification on household food self-sufficiency and adaptation to climate change. At present, such research knowledge and/or insights are generally lacking. Therefore, my PhD research is focused on filling these knowledge gaps.

1.2.Research questions and hypotheses

Research question 1: How can we define and validate sustainable and integrated intensification options of crop production to respond to the need of smallholder farmers in diversified local contexts impacted by climate variability and climate change in Niger?

Research question 2: What innovative combinations of options for AEI perform better in each respective local context?

Hypothesis 1: The agronomic performance of the combined AEI options varies in importance depending on the biophysical and socio-economic conditions of the smallholder farmers (*Options by Contexts* approach, OxC).

Hypothesis 2: Innovative combination of AEI options for AEI that perform better represent pathways to increase the climatic resilience of smallholder farmers of Niger.

Hypothesis 3: The agronomic potential of the dual-purpose cowpea genotypes issued from participatory varietal selection taking account the local contexts is equal or is more important compared to that of the control varieties of the smallholder farmers.

1.3.Objectives

1.3.1. Overall objective

The overall objective of this thesis was to explore innovative combinations of options for agroecological intensification in the Niger low-input millet-based cropping systems with legumes (cowpea) for increased productivity at low cost for subsistence farming systems.

1.3.2. Specific objectives

Specific objectives were to:

1. To identify current bottlenecks constraining agricultural production system of the smallholder farmers and the existing opportunities adapted to the diversity of local family farm contexts.
2. To develop an integrative approach for the choice of the combined AEI options adapted to the diversity of local contexts.
3. To assess the agronomic performance of the combined AEI options across a range of farmers' fields.

4. To evaluate the potential of a range of dual-purpose cowpea genotypes issued from participatory varietal selection process through decentralized trials in the millet-cowpea based cropping systems of Niger.

1.4.Thesis outline

This introduction constitutes the first chapter of the thesis.

Chapter 2 is a literature review that provides an insight on the diversity and key drivers of the family farming as well as the farmers' research network, the options by context approaches and the potential agroecological intensification options. The analysis is used to draw major progress on the use of the participatory research approach and the lessons on the use of some AEI options mostly in the Sahelian context to increase crop productivity and livelihoods and to avert the devastating effects of erratic rainfall.

Chapter 3 presents the research methods used to achieve the objectives of the study. It includes the presentation of the sampling and the baseline survey to characterize the family farms with major focus on key drivers and opportunities (AEI options and local resources availability) to cope with the adverse impacts of the climate change. in Niger. Thereafter, the methodological approach used to co-build an integrative trial design for the best use of the AEI options in the local specific contexts is presented. Finally, I present the decentralized trial approach used to assess the performance of a set of climate-resilient cowpea varieties under different local contexts.

In Chapter 4, part I, the characterization of the family farms with focus on key drivers and opportunities to address these factors is presented. The study was motivated by the need to make a deep diagnosis of the real needs and the constraints faced by the farmers. This study characterizes the structure of the family farms and the opportunities to alleviate the agricultural constraints faced by smallholder farmers in the Centre-South and Western parts of Niger. This part also discusses how the family farms can contribute to food security and to improve the resilience to climate change.

In the part II of the chapter 4, I describe the integrative approach co-designed during this work to test combinations of AEI options to enable farmers using a diversity of innovative practices at the same time in their fields. This study aimed to overcome the discipline partitioning between researchers when they conduct participatory research activities in the fields and the lack of methodology to strengthen the synergy among the researchers and the farmers. The agronomic performance of the combined AEI options across the study locations was then assessed.

The last part III of the chapter 4 assesses the agronomic performance of a specific AEI option i.e., the dual-purpose cowpea varieties selected through the decentralized participatory breeding approach. The decentralized trials approach was used to assess how these varieties adapt to the local contexts and to check whether they are more performant than the local varieties. Furthermore, I drew a general discussion linking the three parts of the findings of the study.

Lastly, in the chapter 5, the major conclusions from this study were prresent. Take-home messages and scientific perspectives for the development of research were also highlighted.

CHAPTER TWO: LITERATURE REVIEW

2.1. Poor crop productivity on smallholder farms in West Africa

West African nations and particularly the Sahel Region are poorly endowed where is a question of soil fertility(Bationo et al., 1998). Thus these inherent characteristics of poor soil fertility remain a major constraint to food security and sustainability of smallholder agriculture in West Africa (Ayoola & Adeniyan, 2006; Bationo et al., 1995; Buerkert & Hiernaux, 1998). Yet in the past, when population pressure was low, farmers shifted from a cultivated site to an uncultivated one before a significant decline in crop yield could set in, thus leaving the fields to replenish soil fertility under natural regrowth. However, with rapid population growth, fallow periods have shortened. Continuous and intensive cropping without restoration of soil fertility has depleted the nutrient base of most soils. For many cropping systems in the region, nutrient balances are negative indicating soil mining (Bationo et al., 1998; Buerkert & Hiernaux, 1998; Ibrahim et al., 2016). Maidment et al., 2015; Salack et al., 2014, 2018) pointed out that following the devastating droughts of the 1970s and 1980s, there is now a return normal to wet conditions marked by extreme weather events. The hybrid character of the rainy seasons including extreme rainfall breaks, wrong onsets and early offset of the seasons represent a major challenge when it comes to crop productivity. Whereas droughts wreak havoc on farming systems, heavy rains cause flooding, which in turn causes asphyxiation of lowland crops through soil waterlogging and erosion of topsoil and micronutrients through runoff. These extreme agro-climatic hazards create tremendous risks for rainfed agriculture in the Sahel (Salack et al., 2015, 2018; C. M. Taylor et al., 2017). In the same way, (Sarr, 2012) pointed out that in the Sahel Region, the most worrying features of climate change are the later onset of the rainy season combined with earlier cessation of the rains, with an estimated decrease of 20% in the length of the growing season. In Niger, (Lona et al., 2019) showed that the current climate change is reflected in rising temperatures and increased variability of rainfall, leading to more frequent extreme events (drought, floods). These changes have negative externalities on natural resources and agro-sylvo-pastoral activities, particularly about the disruption they cause to the agricultural seasons. The same authors pointed out that yields of staple food crops will considerably decrease due to climate change. These challenges are further compounded by the lack of financial means, labour and land constraints faced by the majority of smallholder farmers (Hayashi et al., 2008; Rusinamhodzi, 2013).

Besides this challenge, unreliable rainfall is another major constraint hindering crop production specially rainfed agriculture.

Technical approaches to overcome low soil productivity include (i) mulching with crop residues, (ii) hand-spreading of household wastes, animal manure and compost, (iii) corralling of livestock on fields, (iv) intercropping or rotation of cereals with legumes and (v) application of rock phosphates and soluble N and P fertilizers. Hereby, the proportion of yield increase varies with the agroecological setting (soil types and rainfall) and the rates and frequencies of applying these amendments. However, such technical approaches would be more efficient when they are practised in a combined manner.

2.2. Pathways to advance agroecological transition in the family farming of West Africa: Potential agroecological intensification options in the Sahel context

Agroecological intensification (AEI) is defined as the way of improving the performance of agriculture through the integration of ecological principles into farm and system management. Such improved performance may mean any or all of the following but depending on the context: improved efficiency, increased productivity, enhanced use of local resources, better diets, improved livelihoods, and increased equity with associated increases in resilience and environmental service provision from farmed landscapes (CCRP, 2022; Mockshell & Villarino, 2018). The CCRP described the AEI through a set of seven characteristics which give the concept a stronger focus and an easier application:

- AEI uses local and global knowledge to improve the efficiency and effectiveness of crop, tree, livestock, pest and disease, and soil management;
- It reduces risk and increases productivity through enhanced resilience and adaptation;
- It contributes to the development of local value chains and diverse and nutritious human diets;
- It is based on evolving understanding of biophysical, socioeconomic, cultural, gender, and other contexts;
- It requires cross-sector and multilateral collaboration;
- It is flexible and responsive to local conditions, including farmers' access to inputs and markets;
- It enhances soil health and fertility, increases functional diversity, and reduces pre- and postharvest losses.

AEI option is a type of sustainable agricultural practice that uses biological processes within the farm to increase agricultural productivity. It relies on very few external inputs and instead focuses on recycling nutrients and energy on the farm, such as through mulching, intercropping, crop rotations, and integrated soil and nutrient management. AEI options can potentially contribute to all four dimensions of food and nutrition security, as defined by the United Nations, but there are still limitations to adopting this approach. These limitations include the knowledge of agroecological processes and principles, as well as policy and institutional challenges (Mockshell & Villarino, 2018). To overcome these limitations, an integrative approach taking into consideration all these AE principles can fill the gap. The first exercise may be to explore the potential AEI options of the different contexts in the family farms of Niger. In the next section, we reviewed the importance and the efficacity of some AEI options practised in the family farming contexts of Niger.

2.2.1. Intercropping

In the Sahel, intercropping is practised by combining one of the dominant cereals (maize, sorghum, millet) with cowpeas and/or groundnuts (Steiner, 1982). There are significant differences in the way the intercropping types are implemented depending on the region (Zongo et al., 2016). The effectiveness of intercropping (millet-cowpea or sorghum-cowpea) in weed control compared to monoculture has been proven (Ganeme et al., 2021). Crop associations usually have a very less weed biomass than a sole crop (Pelzer et al., 2020). This effect is probably explained by the stronger ability of the cereal to uptake nitrogen from the soil, thus depriving the weeds of a nutrient essential for their growth. Indeed, the cereal exerts a strong competition for light towards weeds, reducing their development even more (Pelzer et al., 2020). The effects of cereal and cowpea varietal choices on the yields of combined crops have been documented (Ganeme et al., 2021). Intercropping improves soil fertility, mainly due to symbiotic nitrogen fixation at the legume roots, enhances soil water holding, reduces erosion, controls weeds, produces quality fodder, saves energy by eliminating weeding, and saves inputs (Zossou et al., 2021). Thus, its major advantages over a sole crop could probably be attributed to the increased complementary use of growth resources such as nitrogen and light in space and time (Maitra et al., 2021).

Ouédraogo, (2005) showed the importance of intercropping which lies in the diversification of the diet through the introduction of legumes and the improvement of the nutritional quality related to a protein content of 22-24% of cowpea seeds. In addition, Sanou et al., (2016) demonstrated that intercropping (sorghum-cowpea) is more effective than sole cropping in reducing erosion by 80% compared to sorghum alone and by 45-55% compared to cowpea alone.

Many studies have been conducted to characterise the performance and analyse the functioning of intercropping. These studies have shown that yield levels in intercropping are higher or equal to the average of sole cropping. Karim et al., (2016) found that biomass yield, grain yield, weight of hundred grains as well as the harvest index of cowpea were significantly affected by genotypes during two years of experiments. However, there was no significant effect of cowpea density and genotypes on millet grain yields. Perrin & Lefevre, (2019) and Masvaya et al., (2017) showed that the effect of intercropping on yields varied according to the season, while it was little affected by the cropping pattern. Yields were improved in intercropping compared to sole cropping for five seasons but reduced for the other four seasons in both cropping systems. Fidèle Zongo et al., (2021) showed that the sorghum-cowpea intercropping system generally resulted in decreased sorghum yields compared to sorghum monocropping. However, a significant performance of +58% in 2014 and an increase of +10% in 2013 in total grain yields of sorghum and cowpea were recorded compared to sorghum monoculture. High nutrient acquisition efficiency of sorghum combined with cowpea was recorded compared to sorghum monoculture. In addition, Ganeme et al., (2021) found that the yields of sorghum and cowpea intercropping are highly variable and low with an average of 416 kg/ha of sorghum and 240 kg/ha of cowpea. It can be concluded that, on the one hand, the intercropping allows the plants to assimilate essential nutrients according to the ecological requirements of each plant and, on the other hand, if the cultivation practices have proved to have less of an impact on cereal and cowpea yields, then the performance of the system could be improved by diversifying the varieties used.

In short, intercropping plays a key role in Sudano-Sahelian agroecosystems. It, therefore, appears to be a major potential lever for reducing the use of phytosanitary products while maintaining a satisfactory level of yield in terms of quality and quantity (Garba et al., 2018).

However, is any intercropping necessarily relevant? Competition for resources is often the cause of unfavourable effects, but intercropping can also make production more complex from a technical and organisational point of view.

2.2.2. Agroforestry practices with focus on farmer-managed natural resource (FMNR)

Agroforestry is defined as the set of land use techniques where perennial woody species are purposefully exploited on the same land management unit for agricultural production, according to a specific layout or time schedule (FAO, 2015). The FMNR practice has successfully transformed at least three million hectares of land in the South-western region (Larwanou et al., 2006). FEWS-NET, (2019) highlighted that food-deficit forecasts have been less severe in southern areas with high tree densities; this is the case in the southern departments of Mirriah, Matamèye where *Faidherbia albida* densities are very high.

Boube, (2008) showed that depending on the density of the trees, there is a substantial increase in millet grain yields which varies from 32 to 165 kg/ha for an FMNR of less than 3 years, from 59 to 221.5kg/ha for the FMNR of 3 to 6 years and from 120 to 209.5kg/ha for the FMNR of 6 years to more. It can be concluded, on the one hand, that the contribution of organic matter from the trees through litter decomposition and the dynamics of the tree-crop interaction have allowed this substantial increase in yields and, on the other hand, that depending on the duration of this practice, such an increase in yields could be observed. For instance, Illo, (2009) found millet straw yields of 854.83kg/ha and average grain yields under *Faidherbia albida, Piliostigma reticulatum* and *Combretum glutinosum* of 600kg/ha, 435kg and 250kg/ha respectively. It can be inferred that the higher yield under *Faidherbia albida* can be explained by its positive impacts in the intercropping system. The yield under *Piliostigma reticulatum* can be explained by the decomposition of the litter constituting an agroforestry mulch which contributes to the availability of macronutrients and improves agronomic performance (Hien, 2018).

Bado et al., (2022) demonstrated that the 'Ziziphus tree' system increased millet yields and its 'water use efficiency' with 'farmyard manure' and no-fertiliser control. However, millet yields decreased in the 'Ziziphus tree' system with NPK fertiliser alone or combined with 'farmyard manure'. The 'Ziziphus tree' system increased overall annual income by 2-3 times compared to the system without 'Ziziphus'.

Agroforestry therefore contributes to agricultural intensification in a dynamic of crop-wood-animal integration within farms and is one of the potential solutions to be implemented to face the challenge of agroecological intensification of agroecosystems, and to secure the availability of aerial fodder during a good portion of the year. However, how can agroforestry be optimised today to make sustainable use of limited natural resources, preserve tropical forest areas and cope with climate change and market globalisation?

2.2.3. Soil fertility management options

a) Use of farmyard manure

In the Sahel, the application of manure is an age-old practice that consists of transporting manure on a cart to the plot of land at least one month before the rainy season. In the Sahelian part of Niger and the western part of Burkina Faso, under 20% of cultivated land receives organic manure and when it is applied, it does not generally exceed a dose of one tonne per hectare (Sempore et al., 2013). Hence, the search for alternatives to increase the yield of agricultural production is necessary. In addition, Amadji et al., (2007) demonstrated that by applying a minimal dose of manure (45kg/ha/year), cowpea grain yields are increased at least by 114% and 106% respectively for erected and creeping varieties compared to the controls. This suggests that adding a small amount of manure improves cowpea production. Ganry & Thuriès, (2018) highlighted the interest of manure in restoring soil fertility in the semi-arid zone of Africa. These authors found that straw retains 250-260 kg of water/100 kg DM and manure 800-850 kg/100 kg DM. They stated that the supply of N (as well as P and K) to the plant is determined by the organic matter (OM) content of the soil. It can be argued that the more humified OM is, the more it retains water. In sum, the practice of applying manure, especially in minimal doses, increases agricultural yields. In addition to increasing crop yields, the positive effect of manure application is that it lasts longer in the soil to maintain fertility. Mohamed Sidda et al., (2020) estimated that 2t/ha/year of small ruminant manure and 300kg/ha/3 years of Nitrogen Tri Phosphate (NTP) increased millet grain yield by 60.11% and 63.8% with 5t/ha/3 years of small ruminant manure and 300kg/ha/3 years of NTP compared to the control. This indicates that a small amount of manure increases millet yields. Pascal Lompo et al., (2021) demonstrated the combined effects of biochar and manure under millet-based farming in the semi-arid zone of Burkina Faso. The findings showed that soil amendment with biochar had a positive effect on the diameter and grain yield of millet. This would be because the combination of biochar and manure allowed better management of nutrients in the soil and a higher yield of millet.

The reason would be the better management of nutrients in the soil allowed by the combination of biochar and manure which resulted in a higher productivity of millet.

From this, we could state that the use of manure in the Sahel, especially in combination with biochar fertilisation and or compost, could be an alternative for improving the productivity and sustainability of the production system.

b) Micro-dosing fertilisation

Micro-dosing fertilisation means the application of a small amount of mineral fertiliser (2g of DAP, 6 or 3 g of NPK at the first wedding between 15-20 days), either directly applied at sowing time, mixed with seeds before sowing or applied after sowing (at the seedling stage) at the bottom of the plants(Hayashi et al., 2008). This technology was developed to provide farmers with low-cost and accessible fertilisation options. Demisie, (2018) showed that with the introduction of the new micro-dosing fertilisation technique, a substantial increase in yields of up to more than one hundred per cent and farm incomes doubled or more compared to plots without fertiliser and some traditional fertilisation techniques is observed. Somda et al., (2017) estimated that the optimal fertiliser rates are 2g/seed hole for mineral fertiliser and 5t/ha for manure. This combination resulted in a threefold increase in biomass yields compared to the absolute control. The application of mineral fertilisers at different times did not significantly affect yields. Soil pH was increased by about one and more than one unit under 5 and 10 t/ha of manure respectively. Organic Matter (OM) levels, which were below 1% on plots with exclusive mineral fertilisation, increased to 1.08% and 1.26% respectively when 5t/ha and 10t/ha of OM was applied. Assimilable phosphorus levels increased by 21% and 34% with organo-mineral fertilization (5t/ha and 10t/ha OM respectively) compared to the exclusive mineral fertilizer treatments(Somda et al., 2017).

Ibro et al., (2014) showed that sorghum yield from micro-dosing application combined with water harvesting seed holes could reach 700 kg/ha. In addition, Ibrahim et al., (2016) showed that on average, micro-dosing fertilizer treatments at the rate of 2g micro-dose DAP per hectare and 6g NPK per hectare, resulted in 86% and 79% of the grain yields increase recorded when applying 200kg/ha NPK per hectare, in 2013 and 2014 respectively. Thus, the positive effect of fertilizer micro-dosing on millet yield increase resulted from better exploitation of soil nutrients through an early proliferation of lateral roots in the upper soil layer.

Sanoussi et al., (2020) showed that in 2008, an average grain yield of 732 kg/ha and 989 kg/ha was obtained for the control and 6g per hill NPK plots respectively. This concluded that in the low-input millet cropping systems of the Sahel, for the micro-dosing of mineral fertiliser technology to be sustainable in the long term, the improvement and maintenance of soil fertility must be considered as the key issue.

Christian S.F et al., (2019) found that the micro-dosing treatment resulted in the highest average grain (464.1±213.9 kg/ha) and straw (2126±1193 kg/ha) yields of millet compared to the grain (133.3±122.7 kg/ha) and straw (238.5±238.2 ka/ha) controls. This suggests that micro-dose fertilisation can increase crop yields, especially if applied in small quantities. Combining this technique with FMNR could also increase millet yields (Manssour et al., 2020). However, Ibrahim, et al., (2015) showed that by applying only the micro-dosing, the plant draws more nutrients than the amount provided; thus, further depleting the soil. In response, strategies to increase yields while maintaining soil fertility were implemented. These include the coupling of micro-dose fertilisation with organic fertilisers, water conservation techniques etc.

Pale et al., (2021) demonstrated that by combining mineral fertilisers with compost, a substantial increase in millet seed (338 to 502 kg/ha) and straw (657 to 947 kg/ha) yields was observed. This fertilisation technology, coupled with ploughing, increased millet seed yield (266 to 635 kg/ha) and straw yield (381 to 601 kg/ha).

In short, applying micro-dosing alone increases the yield of many crops and it is more beneficial if combined with FMNR. Further, micro-dosing is also beneficial when combined with ploughing.

2.3. Farmers' Research network in advancing agroecological knowledge and practice in the Sahelian context

The last half century has seen significant changes in agricultural research, as demands for research to serve the public good have become increasingly common. To this end, research should focus on indivisible environmental, health, social and economic objectives, as well as on the needs and priorities of smallholder farmers. It also calls on research actors to recognise and learn from different knowledge systems and ways of knowing, including the knowledge of indigenous peoples and farmers who have long recognised the interconnections between food systems, health and the planet.

In the quest for research that will serve the smallholder farmers who rely on rainfed agriculture and have limited access to external inputs, the CCRP developed an approach as a strategy to make research impactful to the small communities. The approach is called Farmer research networks (FRNs). FRNs are farmer groups that are engaged in locally relevant, agroecology research in partnership with researchers, development organizations and/or a broader network of farmers. Its fundamental ambition is to enhance farmers' access to new and old options in a scalable manner, whilst supporting a systematic learning process that allows insights into the interactions of options and contexts to be derived.

To reflect this vision of the FRNs, the CCRP developed a set of principles to guide its work. Individual FRNs are encouraged to take these into account in their development process. Far from being prescriptive, they rather serve as realistic aspirations and inspirations. They are regularly revised as necessary to reflect changes in current understanding and thinking. Each principle encompasses several sub-principles. Here we summarized the three main principles of the FRNs described by Richardson et al., (2022), which well applied could enable advancing the agroecological transition of the smallholder farming systems of the Sahel region:

Principle 1-Farmers: The first principle discusses the importance of engaging diverse farmers in Farmer Research Networks (FRNs). Engaging diverse groups of farmers is important for ethical and practical reasons. Ethically, it is important to ensure that all people have access to the benefits of agricultural research and development and that everyone's perspectives are valued. Practically, it ensures that research is relevant to the needs of all farmers and that the results are not biased towards any particular group. It also helps to ensure that all stakeholders have a sense of ownership in the research process, leading to more successful implementation and innovation. The McKnight Foundation, which initiated the Collaborative Crop Research Program, has a commitment to diversity, equity, and inclusion, which is why engaging diverse farmers is crucial.

Principle 2-Research: The second principle of the FRNs approach is to conduct research that is both practical and useful to farmers and which is carried out with sufficient rigour to produce credible evidence of relevance to agroecology. This goes beyond the traditional approach of searching for the best option and instead focuses on innovation based on an understanding of agroecology principles so that farmers and their counterparts can refine practices that work for them in their specific social and biophysical contexts. The research-related principles also require that study designs are adapted over time, based on reflection with farmers, through research plans that are co-developed by the principles of farmer engagement. Furthermore, the research principles emphasize the importance of recognizing various forms of knowledge, including local or indigenous knowledge as well as scientific knowledge from different disciplines. Thus, the idea of cognitive justice is also relevant, which means that authentic participation requires that diverse epistemologies and methodologies are given enough attention and respect.

Principle 3-Networks: The third FRN principle focuses on the importance of networks in sharing farmer innovations and knowledge about agroecosystems. Agroecology is the study of the interaction between plants, animals, and the environment in agricultural systems. Food security is the state of having reliable access to a sufficient quantity of affordable, nutritious food. Thus, collective efforts are required to affect changes at a population, landscape, and ecosystem level. Therefore, networks are essential to involve a wide range of stakeholders in the process of generating knowledge and sharing it with large numbers of farmers and other actors. These networks should be effective, facilitating the circulation and sharing of learning and innovations among farmers and other stakeholders. Moreover, different stakeholders should be involved to foster these co-learning processes.

Furthermore, in the context of smallholder agriculture, FRNs could enable AEI options to be adapted in diverse ways across a wide range of contexts.

2.4. Diversity of smallholder farming systems in the Sahel region

The presence or absence of livestock and/or the number of livestock in many parts of West Africa often distinguishes the dominant farming system, although millet and cowpea seem to be the staple crops. Cattle are considered important for providing draught power, milk, manure, and meat as insurance and a symbol of wealth (Mariana Cristina, 2008; Thornton & Herrero, 2001). Millet & sorghum and cowpea are important food security and cash crops respectively for the majority of West African smallholder farmers. The combination of biophysical factors such as soil type and climate, and socio-economic factors such as resource land ownership and access to markets determines the focus of farmers' production in any given community. At the farm level, the limited labour and inadequate resources such as cattle manure or chemical fertilisers often oblige farmers to apply fertilisers only to limited portions of the farm each year, resulting in heterogeneous soil fertility conditions in the fields (Mapfumo et al., 2005; Tittonell et al., 2008). The success of intensification options for agricultural production is therefore largely dependent on site-specific recommendations that take into account local constraints and opportunities to improve crop yields(Rebecca Nelson, 2016). Options by context approach to better optimise productivity in the Niger Republic is crucial. To understand this, I developed an integrative approach taking into consideration the specific contexts (Chapter 3, part II) and thereby I tested the combined AEI options (Chapter 4, part II) including the climate-resilient cowpea varieties (Chapter 4, part III) to identify those that are adapted to each local context.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Study locations

The study locations are part of the Sahelian zone across three regions in Niger (1° 42' 40" E to 8° 23' 30" E and 12°52'50" N to 18° 13'30" N). These regions are: Dosso, Maradi and Tillaberi.

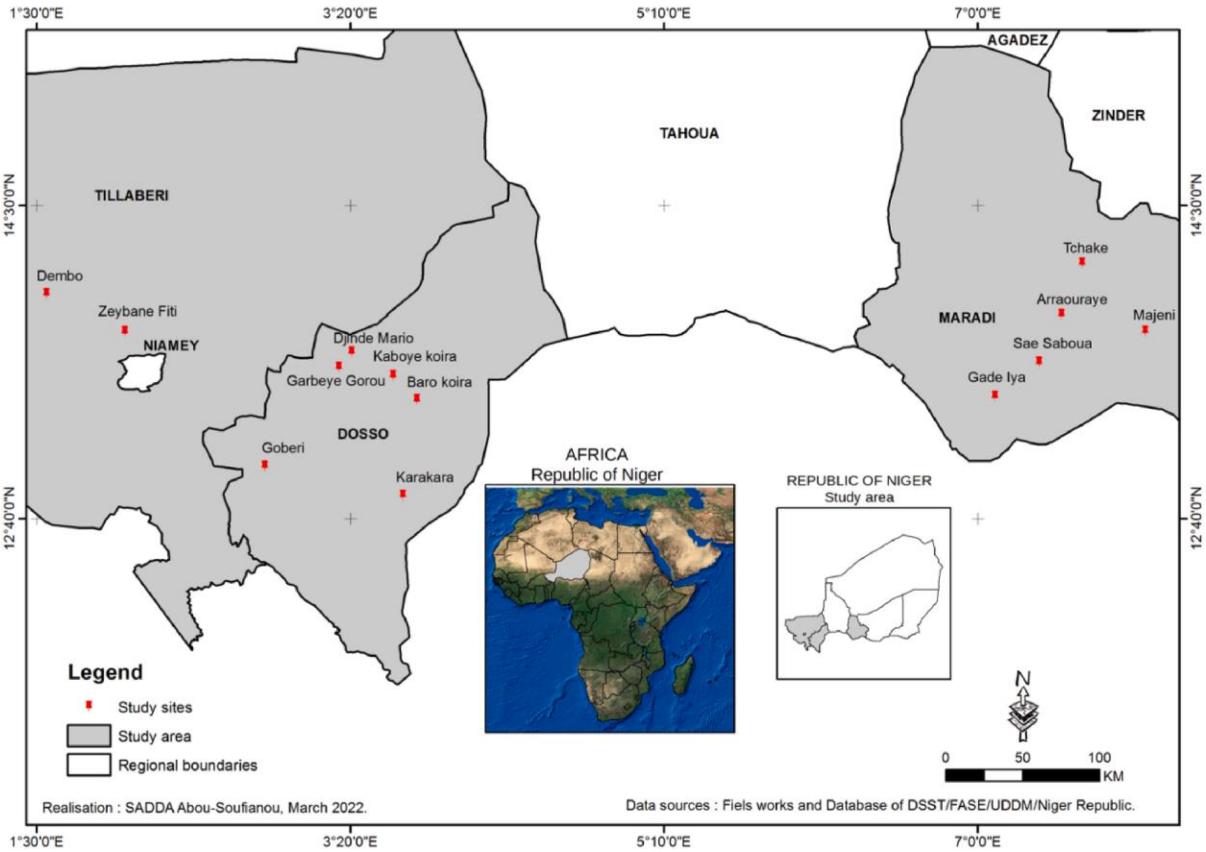

Figure 1: Locations of the study

Source: Hamadou et al., (2023)

Overall, in Niger, the climate is generally classified as semiarid tropical with a long dry season (November to May) followed by a single rainy season (from June to October).

In the Dosso region, the spatial rainfall pattern (Figure 2) clearly shows a significant South-North gradient, with cumulative rainfall ranging from an average of 800 mm around Dendi in the extreme south to 350 mm in the extreme north, which explains why the region is referred to as a Sahelo-Sudanese zone. This is demonstrated both by the spatial distribution of average rainfall from 81-2010 and by the average rainfall for the period 2011-2016(ANADIA, 2018).

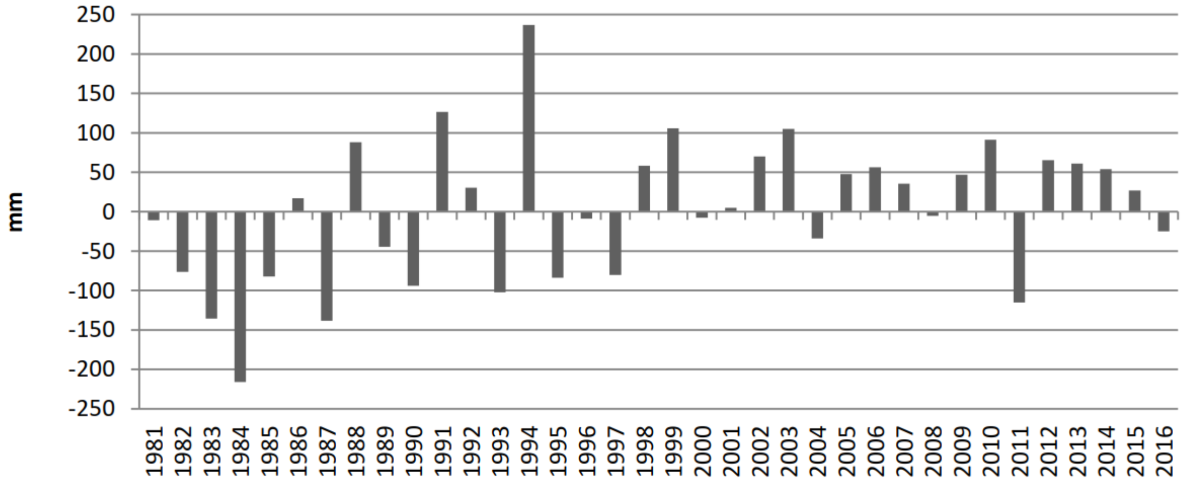

Figure 2: Rainfall evolution of the Dosso Region from 1981 to 2016: Differences of the annual average vs the average of the 1981-2016

Source: (ANADIA, 2018)

Figure 3 shows that from the 1980s to the mid-1990s the climate was generally mild with below average temperatures. However, after 1997, maximum temperatures in the region experienced a continuous and sustained increase and have continued to do so except for a slight attenuation during the very wet years of 2008, which is an artefact of the cooling of the Pacific basin and does not change the trend of the sustained increase. Average temperature excesses in the late 2000s reached more than 0.5°C (up to 0.8°C in 2010 and almost 1°C in 2011), reflecting a significant and persistent warming in an ever-changing climate(ANADIA, 2018).

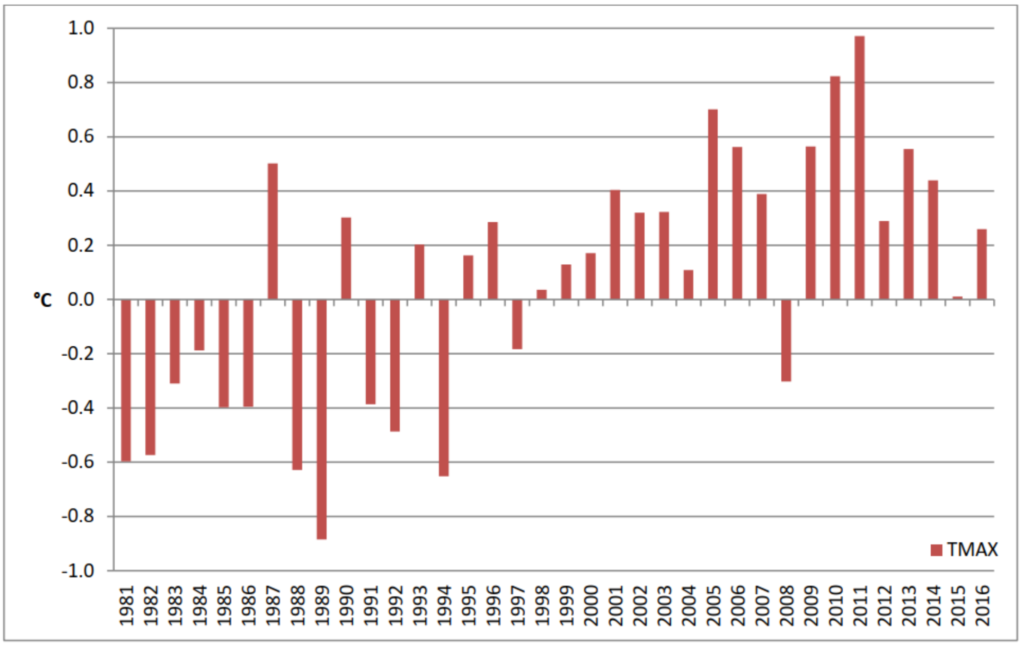

Figure 3: Evolution of the maximum temperature average in the Dosso Region: Difference of the annual average vs the average of the 1981-2016

Source: (ANADIA, 2018)

Nevertheless, the evolution of minimum temperatures (Figure 5) in the Dosso region shows a similar pattern to that of maximum temperature, but with the start of the sustained rise occurring later. The largest increase compared to the 81-2010 average of around 0.9°C is observed in 2016.

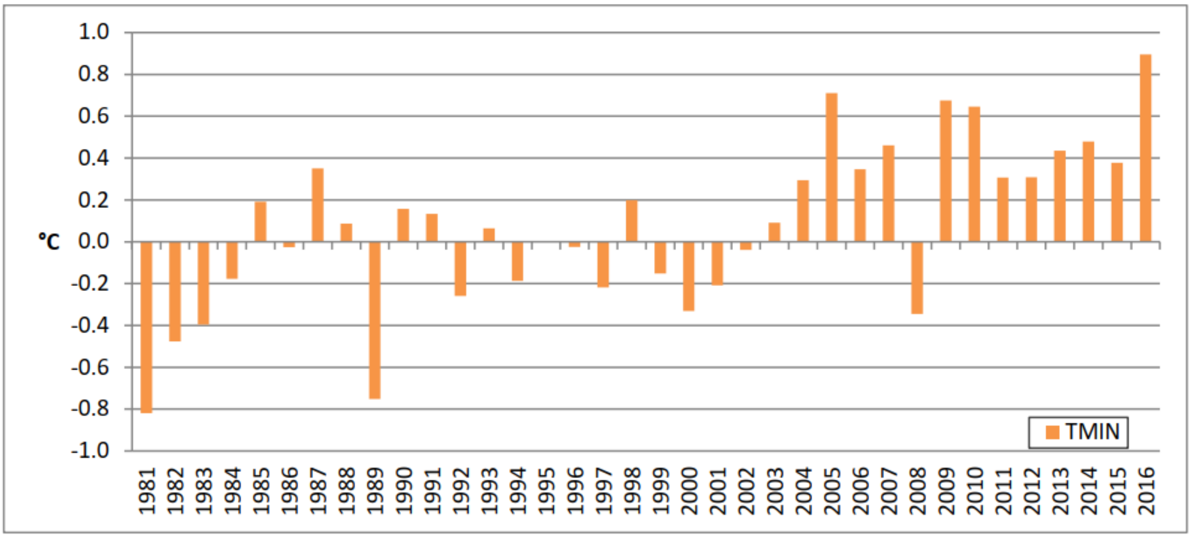

Figure 4: Evolution of the minimum temperature average in the Dosso Region: Difference of the annual average vs the average of the 1981-2016

Source: (ANADIA, 2018)

The Maradi region has a Sahelian climate with a transition to a desert climate in the north. It is characterised by two distinct seasons: A rainy season, from 4 to 5 months (May-June to September-October). A dry season, for the rest of the year. Moreover, the temporal variations in rainfall amounts in the region are significant. The standard deviation of total rainfall is 91 mm with an average annual rainfall of 426 mm (1960-2020). The annual extremes over this period are 214.7 mm in 1987 and 719.6 mm in 2018 (Figure 5)[1].

[1] In these figures (Fig.5-Fig.8), the legends and contents are in French, as the data are secondary. Hence, read "Precipitations" as Rainfall and consider the numbers with commas as decimal numbers in both Fig. 6 and Fig.8

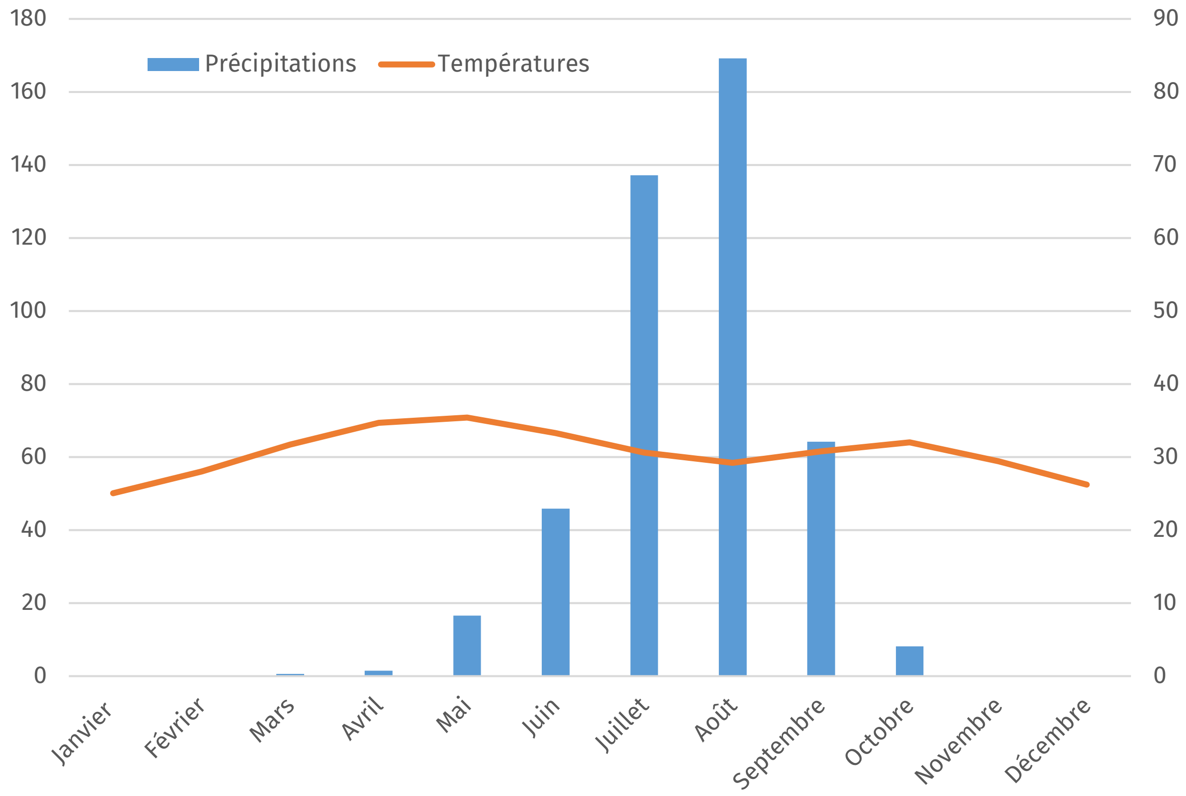

Figure 5: Umbro thermal diagram of the Maradi weather station (1960-2020)

Source: (DMN, 2022)

The extreme minimum and maximum average temperatures are respectively 19 °C and 43.2 °C (Figure 6).

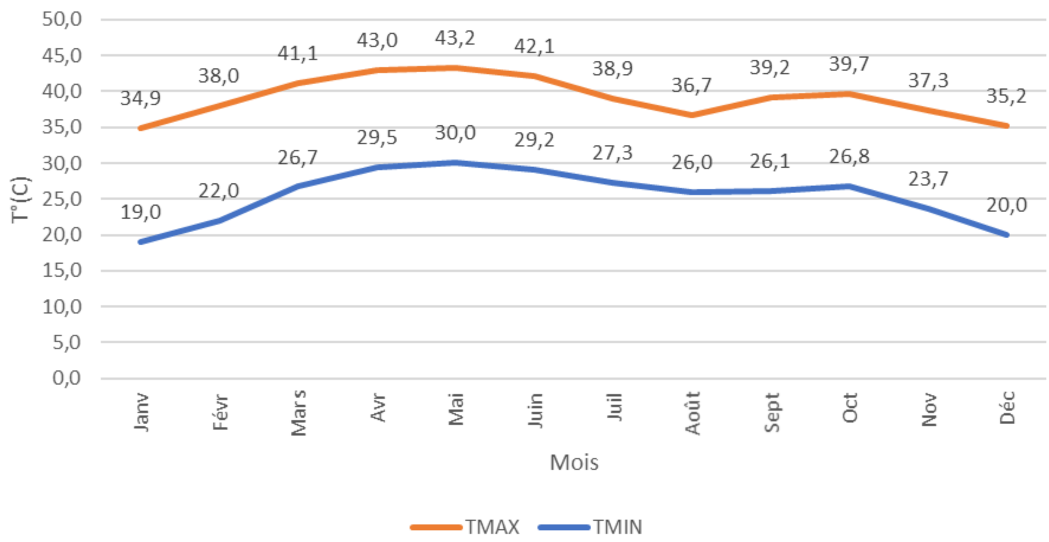

Figure 6: Average monthly temperature extremes over the period 1960-2020 for the Maradi region

Source: (DMN, 2022)

Finally, the Tillabéri region is characterised by a short rainy season (June to September) and a long dry season (Figure 6). Moreover, about 60% of rainfall occurs in July and August. In this region, the standard deviation of cumulative annual rainfall is 117mm for an average annual rainfall of 421mm (1960-2020). The annual extremes over this period are 214.6 mm in 1987 and 693.2 mm in 1961 (Figure 7).

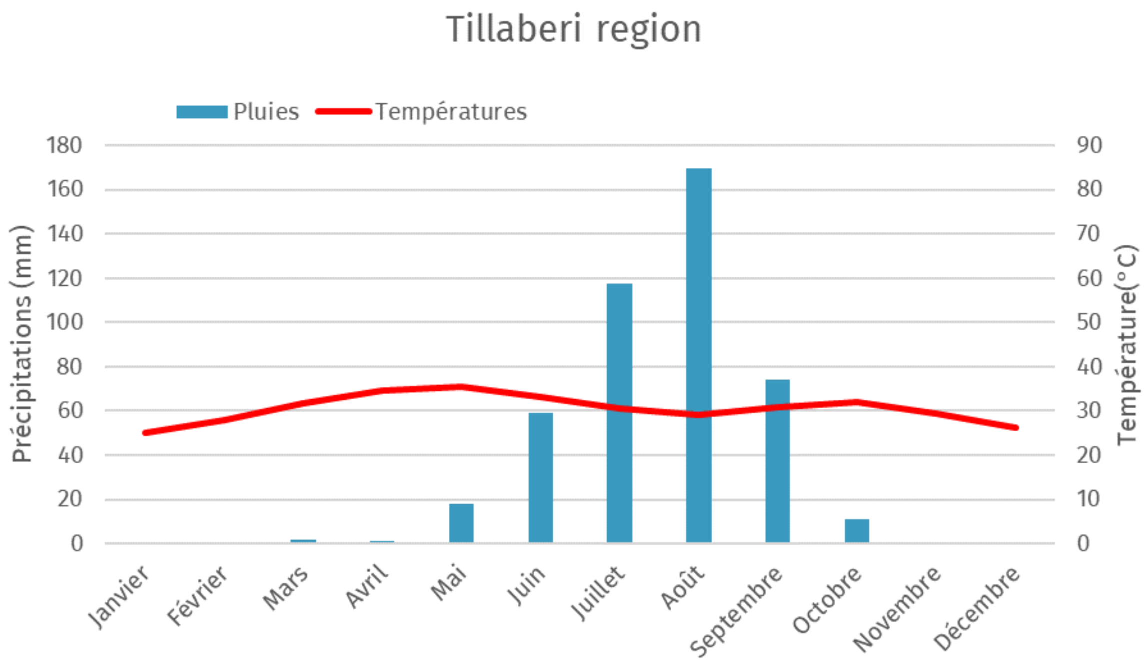

Figure 7: Umbrothermal diagram of the Tillaberi weather station (1960-2020)

Source: (DMN, 2022)

The extreme minimum and maximum temperatures are respectively 21.4 °C and 45.1 °C (Figure 8).

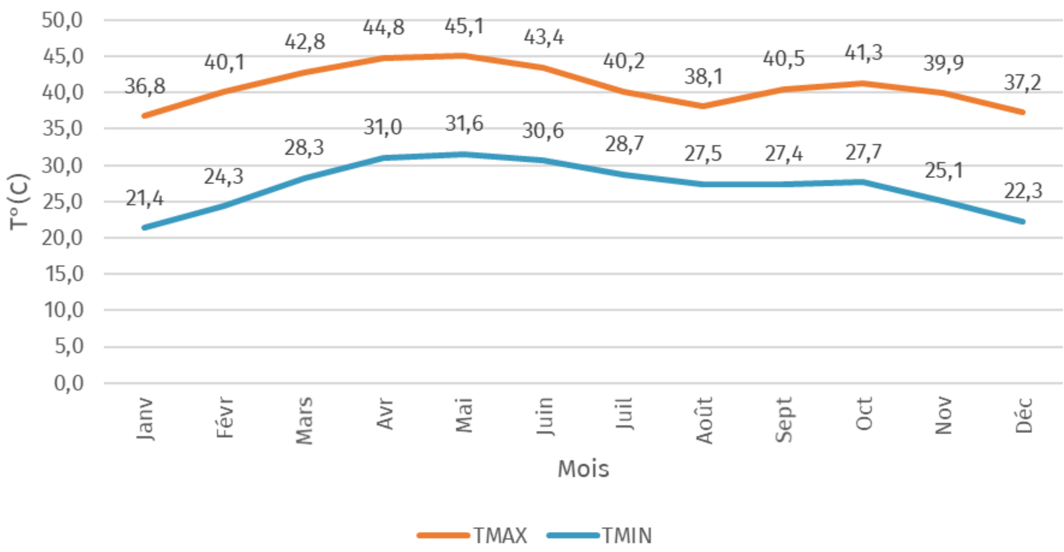

Figure 8: Average monthly temperature extremes over the period 1960-2020 of the Tillaberi region

Source: DMN, (2022)

The soils across the study locations are sandy, very deep reddish and well drained (Sadda et al., 2021). The study locations are mainly characterized by the family farming practices and animal husbandry. Agriculture is mostly rainfed based on pearl millet [*Pennisetum glaucum (L.) R Br.*] and sorghum [*Sorghum bicolor (L.) Moench*.] as well as cowpeas [*Vigna unguiculata subsp. unguiculata (L.) Walp*.] and groundnuts (*Arachis hypogaea L*.).

Farmers participating respectively in the survey baseline, the process of co-constructing the integrative experiment design and the farmers' decentralized trials were members of the two farmers' organisations i.e., FUMA Gaskiya and Mooriben. Their selection was done based on the motivation and volunteerism, including men and women, farmers of various economic levels, without applying a particular quota but remaining as inclusive as possible.

Villages sampling among the study locations, specific sets of villages were sampled based on specific study objectives (Table 1). Thus, for the survey, six villages were sampled with the assistance of these two farmers' federations. For the integrative trial design, I considered four villages. Finally, the assessment of a range of dual-purpose cowpea varieties through the farmers' network, fifteen villages were considered. The names of the study locations are fully described in the methods section.

Table 1: Sampling of the study locations

Region	Village	Survey	Integrative trial design	Assessment of a range of dual-purpose cowpea varieties
Maradi	Arawraye			x
Maradi	Boussaragui			x
Maradi	DaraAmadou			x
Maradi	Gade Iya	x		x
Maradi	Gwassale		x	
Maradi	Mayara			x
Maradi	Maiki			x
Maradi	SarkinBindiga			x
Maradi	Saye Sabuwa	x	x	x
Maradi	Tchake	x	x	x
Maradi	Warzou			x
Dosso	BaroKoira			x
Dosso	DjindeMario			x
Dosso	Garke		x	
Dosso	Karakara	x		x
Dosso	Kaboye Koira	x	x	
Tillabery	Dembo			x
Tillabery	Zebane Fiti	x		x

3.2. Research methods and data collection

The methodological approach was divided into three to achieve the specific objectives of the study. Part I described the method used for the survey baseline on family farms characterization and tailoring the potential AEI options. Part II presented the methodology used to co-build the integrative trial design and to assess the agronomic performance of the combined AEI options. Finally, the part III described the method used to assess a set of dual-purpose cowpea varieties through decentralized trials under different local contexts.

3.2.1. Part I: Survey baseline for the family farms characterization

This survey attempted to achieve the specific objective 1 of the study.

3.2.1.1. Study location sampling

Two-stage sampling procedures were used: (i) the selection of the study locations, and (ii) the family farms of each location. The number of villages (study locations) was balanced based on the intervention zones of the CowpeaSquare project and the affiliation status of the village to one of the two farmers' federations (FUMA Gaskiya in the Centre-South and MOORIBEN in the West). Thus, 6 villages were selected: three in the Maradi region which are affiliated to FUMA (Gade Iya, Saye Sabuwa and Tchake) and the remaining three are affiliated to the MOORIBEN: two villages (Kaboye Koira and Karakara) located in the Dosso region and one village (Zebane Fiti) in the Tillabery (Fig.1). These villages also covered a north – south ecological gradient (the north being more arid). The respondents comprised of 20 farmers per village except the village of Gade Iya (only 10 farmers were surveyed because of the unforeseen circumstances during the data collection) and Karakara (19 farmers). Farmers were randomly selected in each village. Thus, the questionnaire was administered to 109 selected farmers across the 6 selected villages.

3.2.1.2. Questionnaire development and data collection

A baseline survey was carried out in the six selected villages between November and December 2021. The questionnaire used to collect the data consisted of three main parts (check annex 3 for further details of all the variables used for the survey). In the first part, i.e., the respondent's identification in the name of the family farm, household identification data (name of the head of the family farm, sex, marital status, type of education, number of kids…) as well as information on the geographical position, and affiliation status to the farmers' organizations were collected. In the second section, i.e., family farms characterization, I collected data on the source of income (main and second activities), household composition, the presence/absence of the main field ("Gandou") led by the head as well as the presence/absence of the field led by female in the family farm the agricultural land owned by the household, its location in relation to the household's concession, the method of acquisition, land ownership, farm size, farming activities, livestock size. Nevertheless, I used the survey database of (Hamadou et al., 2023) to extract the crop species diversity of the six villages alone Finally, the third part focused on farmers perceived key drivers hindering agricultural production in the family farms as well as the existing options for agroecological intensification (AEI) to enhance crop productivity. Smartphones were used during data collection as we created a Kobo Collect form.

3.2.1.3. Statistical analysis

Descriptive statistical analysis combined with the FAMD (Factor analysis for the mixed data), and the Pearson Chi-Square test were used to characterize the family farms and to tailor the key drivers of family farms as well as the main agroecological intensification options that farmers considered as adaptation measures. Thus, data were disaggregated and analysed for each study location accordingly and similarly data were averaged when generalization was needed for the six selected villages. For instance, data were averaged with respect to the family farms characterization whereas data on the exploration of both the major key drivers and AEI options were analysed separately for the study locations. Descriptive statistics with (Epidisplay & Psych R packages) was used to generate means, proportions and or frequencies for the qualitative data (presence/absence of the fields led by female, presence of Gandu, the constraints types…). While the FAMD was performed to analyse all the datasets (quantitative and qualitative) in order to explore the similarity between observations by taking into account mixed variables. For this, the following R packages FactoMineR, factoExtra, factoshiny and missMDA were used. Pearson Chi-Square test was used to assess the relationship between the gender and the presence of MF and the WF. Ggplot2 and fsmb packages were used for graphical representation of the AEI options identified in each study location.

3.2.2. Part II: Co-designing the integrative trial design across the pilot sites

This part of the thesis was supported by the transdisciplinary team of TAE Niger project (Agropolis Foundation grant).

3.2.2.1. Steps in the process of designing the integrative trial

The design process consisted of four steps: Step 1. Defining the AE options. Step 2. Establishing the combined AE options to be tested in the integrative trial. Step 3. Setting up a statistical experimental design to implement the integrative trial, Step 4. Implementing the integrative trial by supporting and documenting the adaptation to local constraints without distorting the experimental design.

3.2.2.2. Surveys and measurements of the integrative trial

The integrative trial was carried out in four experiment sites during the 2021 cropping season. Plot sizes were not the same in the four experiment sites due to the unavailability of sufficient spaces and the logistic constraints coming up when implanting the trials in the Centre-South. In the Western part (Garké & Kaboye Koira sites), the size of each of the eight plots was 90 × 100 m while in the Centre-South (Sayé Sabuwa & Gwassalé sites), the size of each plot unit was 30 × 100 m.

Seeds of the pearl millet local variety and the DAP mineral fertilizer were purchased from one farmers' union in Falwel and used in all the trials. Farmers supplied the decomposed mixed manure. The cowpeaSquare research project supplied the seed of the two dual-purpose cowpea varieties used in all the trials. These two varieties are short-duration (75-80 days) and dual-purpose varieties (Cowpesquare database). The rate of the decomposed and mixed manure application used in the trials was 100g per seed hole and it was applied at the time of sowing while the rate of DAP application was 2g per seed hole as a micro-dose. Before sowing, farmers together with the technician of each village ploughed the fields and laid out the experiments. Pearl millet was sown at 1m × 1m and cowpea was planted between pearl millet rows in the intercrop while the spacing was 09cm× 40cm for the sole cowpea crop. Pearl millet was thinned at 15 days after sowing with three plants per pocket/seed hole and three grains of cowpea were sown. The plots were kept weed free by an initial weeding 15 days after sowing and ridged 25 days after sowing. All the plots were also weeded twice (15 days and 45 days after sowing). Technicians from farmers federations on the experiment sites managed the trials with farmers.

To help understanding the agronomic performance of the combined AEI options, several data types were recorded: (i) rainfall data, (ii), crop yield components, and (iii) participatory assessment using a range of criteria.

In each experiment site, a technician collected daily rainfall data with a manual rain gauge. At harvest, crop yield components were determined from each plot. These crop yield components were: grain yield, haulm yield, the weight of 100 grains for cowpea and biomass yield for millet.

The participatory assessment (farmers' field discussions) of the combined AEI options was conducted using both a set of criteria and the voting system: (i) green card: representing a higher appreciation of the plot, (ii) yellow card: a moderate appreciation of the treatment plot and (iii) red card: representing a lower appreciation of the combined AEI options tested.

3.2.2.3. Statistical data analysis

The experimental treatments of the design were the combined AEI options defined in the design process. Each one was a plot within the trial in each study location. Plots attributes were A1, A2, A3, A4, B1, B2 B3, B4 as described in the Table.2.

The dual-purpose index (DPI) of cowpea was calculated as follows:

$$DPI = (3 \times GY) + HY \tag{1}$$

where GY is the cowpea grain yield and HY is the cowpea haulm yield (Saidou AA, unpublished).

Participatory assessment data enabled the computation of the multi-criteria index (IVM) of the combined AEI options. The following formulae were used to determine the IVM (Saidou AA, unpublished).

$$IVS = (2\times GC) + (1\times YC) - (2 \times RC) \tag{2}$$

$$IVSadj = \sum IVS - \frac{mean\ (IVS)}{sd\ (IVS)} \tag{3}$$

$$IVM = mean[IVSadj] \tag{4}$$

Where IVS was the index of simple voting, GC the green cards, YC the yellow cards, RC the red cards, IVSadj was the adjusted IVS index and IVM was the multi-criteria index. The IVS was adjusted to IVSadj to integrate all the different criteria with a statistically comparable distribution.

ANOVA was used to estimate the main effects of individual AEI options on yield components of the two cowpea varieties while a linear mixed model was constructed to fit the crop yield data to determine the effects of combined AEI options. The experimental treatments were considered fixed effects and the trials of the four study locations were treated as random effects (Allan & Rowlands, 2001).

The statistical analysis was performed with R software (R Development Core Team, 2005) and its implementation on RStudio was used to ease the data manipulation.

3.2.3. Part III: Assessing the range of cowpea dual-purpose varieties through farmers' network

3.2.3.1. Description of the experiments

Large on-farm trials named "*decentralized trials*" were carried out during the main cowpea and pearl millet growing season, from June to October 2022. Participating farmers originated from the fifteen selected villages (Fig.1): In the Centre-East, ten villages were considered: Arawraye, Boussaragui, Dara Amadou, Gade Iya, Mayara, Maiki, Sarkin Bindiga, Saye Sabuwa, Tchake, Warzou. In the Western part, five villages were selected: Baro Koira, Djinde Mario, Karakara, Dembo and Zebane Fiti. A total of 303 trials were planted by 20 farmers in each village except the villages of Gade Iya and Karakara with 18 and 25 farmers respectively.

Each sole crop trial was comprised of two plots of 10 × 10 m each: a control plot and a plot to test the selected cowpea variety/genotype. The control plot was the most preferred cowpea variety of each farmer. Participating farmers managed the trials with the help of technicians to ensure that the operations for both plots were conducted in a timely manner. Each farmer hosted one single, non-replicated trial with the two plots in the same field and practiced his own management system for fertilizer application, weeding. Any pest and disease control were not done in the two plot types as instructed during the trial implementation.

The selected cowpea genotypes were composed of the newly created genotypes of cowpeaSquare project labelled as CWS-RILs and the accessions (CS) collected in 2016 from various research institutes and seed compagnies.

Further details on the selection process of the CS and the CWS cowpea genotypes were given in the Fig.10 and Fig.11 respectively.

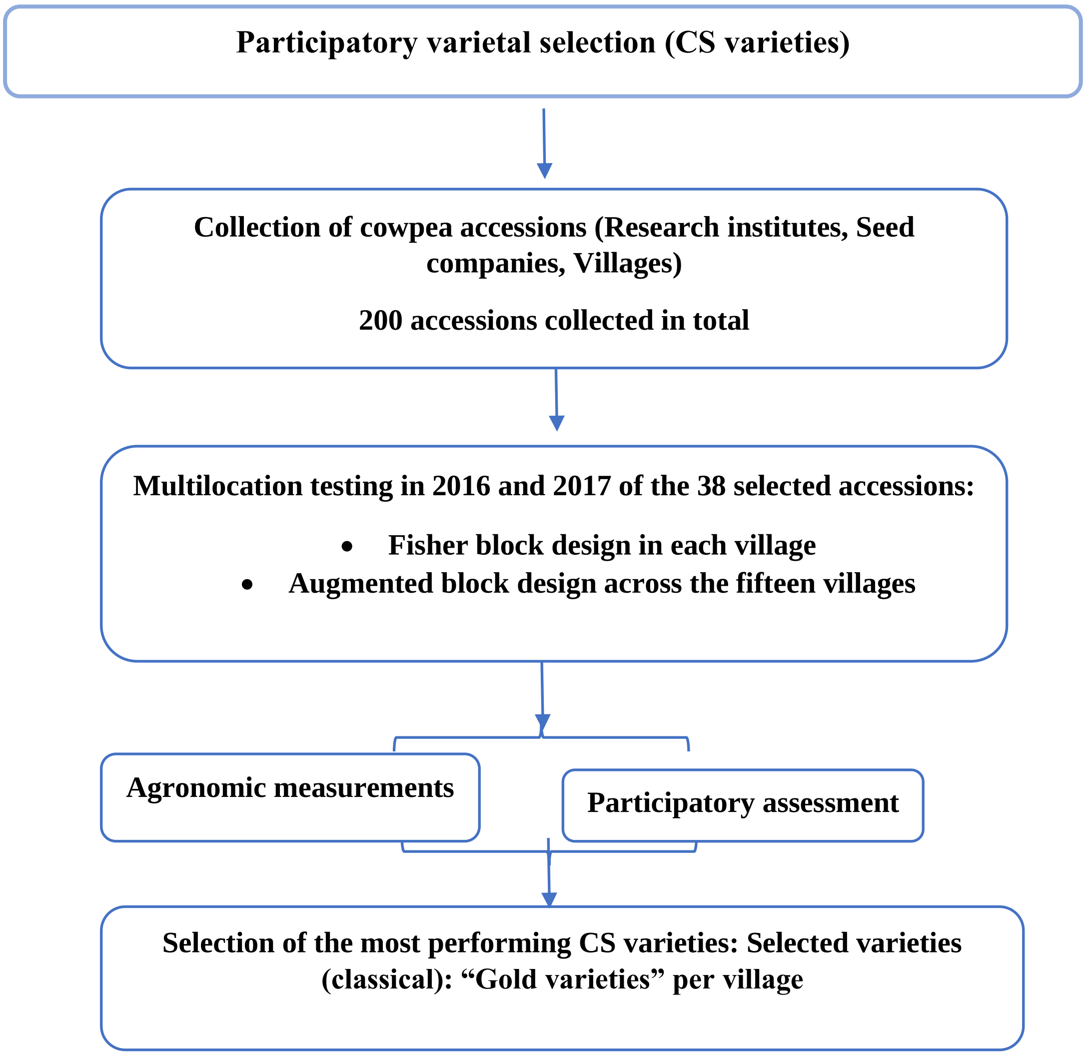

Figure 9: Pathways of developing the selected cowpea varieties (classical) for farmers across the fifteen study locations

Source: (CowpeaSquare project, 2023)

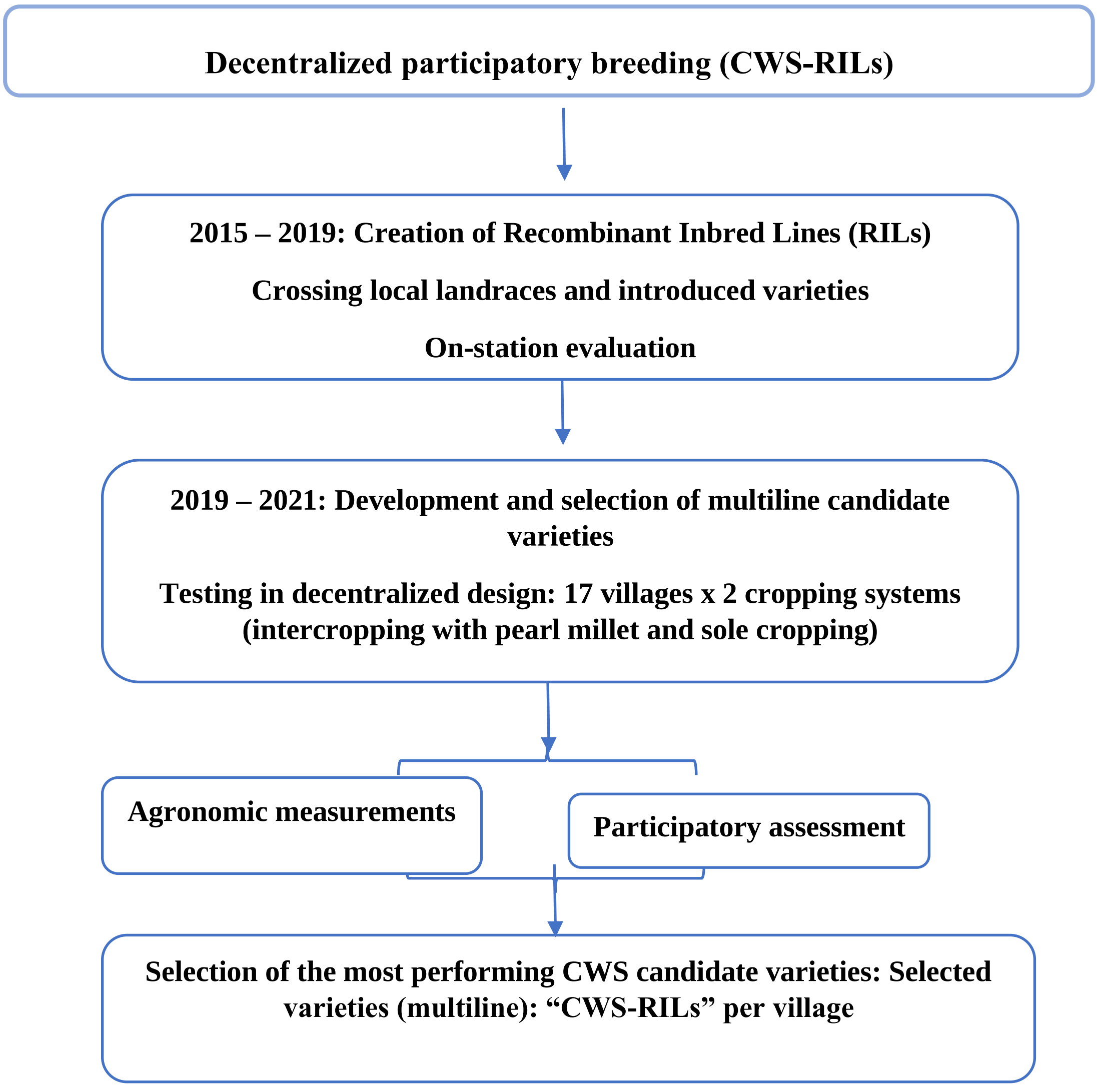

Figure 10: Pathways of developing the selected cowpea varieties (multiline) CWS-RILs for farmers across the fifteen study locations

Source: (CowpeaSquare project, 2023)

The characteristics of the classical cowpea varieties and the candidate multiline cowpea varieties were described respectively in the table.2 and table.3.

Table 2: Main characteristics of the selected cowpea varieties (classical)

Varieties Codes	Origin	Original name	Origin of seeds	Grain colour	Cycle duration	Average yield
CS001	Djinde Mario	Dan gondale	CowpeaSquare	White	Intermediate	Common yield
CS012	Goberi (Niger)	Doungouri Beri	CowpeaSquare	White	Intermediate	Common yield
CS052	DaraAmadou	Dan Watsatsa	CowpeaSquare	White	Intermediate	Common yield

CS127	INRAN (Niger)	Botsotsuwa Ishirnawa	CowpeaSquare		Early	Very high yield
CS133	Niger	Lakkade	CowpeaSquare	White	Late	Common yield
CS134	INRAN (Niger)	NELOC-164	CowpeaSquare	White	Early	Very high yield
I90 (Mai jan hanci)	IITA (Nigeria)	IT 90K372-1-2	CowpeaSquare	White	Early	Very high yield
KVX	INERA (B. Faso)	KVX 30-309-6G	CowpeaSquare	White	Early	Very high yield

Source: (CowpeaSquare project, 2023)

Table 3: Main characteristics of the selected candidate varieties of cowpea (multiline)

Candidate varieties	Cycle duration	Crop yield category	Grain colour	Eye colour	Eye diameter	Seed coat trait
CWS-RIL-38-17	Intermediate	Common yield	Light red	Marron	Thick	Smooth
CWS-RIL-38-2	Intermediate	Common yield	White	Marron	Thick	Rough
CWS-RIL-38-20	Intermediate	Very high yield	Light red	Marron	Thick	Smooth
CWS-RIL-38-3	Early	Common yield	White	Marron	Thick	Rough
CWS-RIL-38-34	Intermediate	Common yield	White	Marron	Thin	Rough
CWS-RIL-38-35	Early	Common yield	White	Marron	Thin	Rough
CWS-RIL-38-36	Late	Common yield	White	Marron	Thin	Rough
CWS-RIL-38-37	Intermediate	Very high yield	White	Marron	Thin	Rough
CWS-RIL-38-38	Early	Very high yield	White	Marron	Thin	Rough
CWS-RIL-38-4	Late	Common yield	White	Marron	Thick	Rough
CWS-RIL-38-43	Intermediate	Common yield	White black spotted	Marron	Thin	Rough
CWS-RIL-38-44	Early	Common yield	White black spotted	Marron	Thin	Rough
CWS-RIL-38-45	Late	Common yield	White black spotted	Marron	Thin	Rough
CWS-RIL-38-46	Intermediate	Very high yield	White black spotted	Marron	Thin	Rough
CWS-RIL-38-48	Intermediate	Common yield	White marron spotted	Marron	Thin	Rough
CWS-RIL-38-49	Early	Common yield	White marron spotted	Marron	Thin	Rough
CWS-RIL-38-5	Intermediate	Very high yield	White	Marron	Thick	Rough

CWS-RIL-38-50	Late	Common yield	White marron spotted	Marron	Thin	Rough
CWS-RIL-38-52	Early	Very high yield	White marron spotted	Marron	Thin	Rough
CWS-RIL-38-56	Early	Common yield	White	Black	Thin	Rough
CWS-RIL-38-6	Early	Very high yield	White	Marron	Thick	Rough
CWS-RIL-38-7	Late	Very high yield	White	Marron	Thick	Rough

Source: (CowpeaSquare project, 2023)

3.2.3.2. On-farm trials measurements

Before starting the data collection, farmers were asked to keep their fields intact (without harvesting) until the visiting mission carried out agronomic measurements and collected data for analysis according to scientific standards. First, the control plot (10 × 10 m) was demarcated before the harvest in each farmers' fields near the plot of the selected cowpea genotype. Secondly, both the weights of pods and haulm of each were measured using the CAMRY EMPERORS scale. These weights were then converted into pod and haulm yield (kg/ha). The weights of grain yield were not measured because of the logistic constraints and each farmer kept the production of the variety he tested since he wishes to cultivate it during the next rainy season. Kobo collect form was created to facilitate data collection and handling and thus smartphones were also used during the field measurements.

Rainfall data from the nearest rainfall stations of each study locations were collected from either the regional directorate of the ministry of agriculture or the farmers' federations. These data helped in the interpretation of the results.

3.2.3.3. Statistical analysis

Prior to data analysis, Excel was used to process raw data to have matrix of data suitable to perform the analysis. Statistical analysis of the data was done separately for each study location because I do not consider site effects as I dealt with the OxC approach. In each village, the cowpea genotype used was specific. Thus, the Wilcoxon paired test was performed to compare the pod and haulm yields of the selected cowpea (CS and or CWS-RILs) with the same yield components of the control varieties used by the farmers of each village. This test was done separately in three different ways using subset and *droplevel* functions in R: (a) a Wilcoxon test across the fifteen villages where I have not set any rule, (b) a case study of the selected varieties tested for at least 20 farmers per village and (c) the same test for a case study of the most used cowpea variety as control for at least 20 farmers all villages together. All the analyses were done using R (R Development Core Team, 2005;).

Graphical representations were drawn to compare the yields of both selected varieties and the control varieties by using the boxplot (R package ggplot2, ggpubr and gridExtra).

The dual-purpose index (DPI) was computed using the following formula:

$$DPI = (3 \times PY) + HY \tag{5}$$

where PY is the cowpea pod yield and HY is the cowpea haulm yield (AA Saidou, unpublished).

The delta pod yield and delta haulm yield were computed with the following formulae:

$$\Delta 1 = PY1 - PY2 \tag{6}$$

Where Δ1 is the delta pod yield, PY1 is the average pod yield of the selected varieties and PY2 the average pod yield of the control varieties

$$\Delta 2 = HY3 - HY4 \tag{7}$$

Where Δ2 is the delta haulm yield, HY3 is the average haulm yield of the selected varieties and HY4 the average haulm yield of the control varieties.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Results

4.1.1. Part I: Characterizing family farms and their constraints and AEI options for innovation: A case study from the Sahelian zone, Niger

This part I presents the results of the specific objective one of the study.

4.1.1.1. Family farms characteristics with focus on farming activities and resources endowment

The average age of the family farms member surveyed across the study location was 47 years old. The minimum age was of the surveyed family farms member was 17 years old while the maximum was 78 years old (Fig.11a). Further, the majority of the surveyed family farms member are married (95 over 109) (Fig.11b) and there are in majority male (81) (Fig.11c) and the family farms encompass averagely 3 households (Fig.11d).

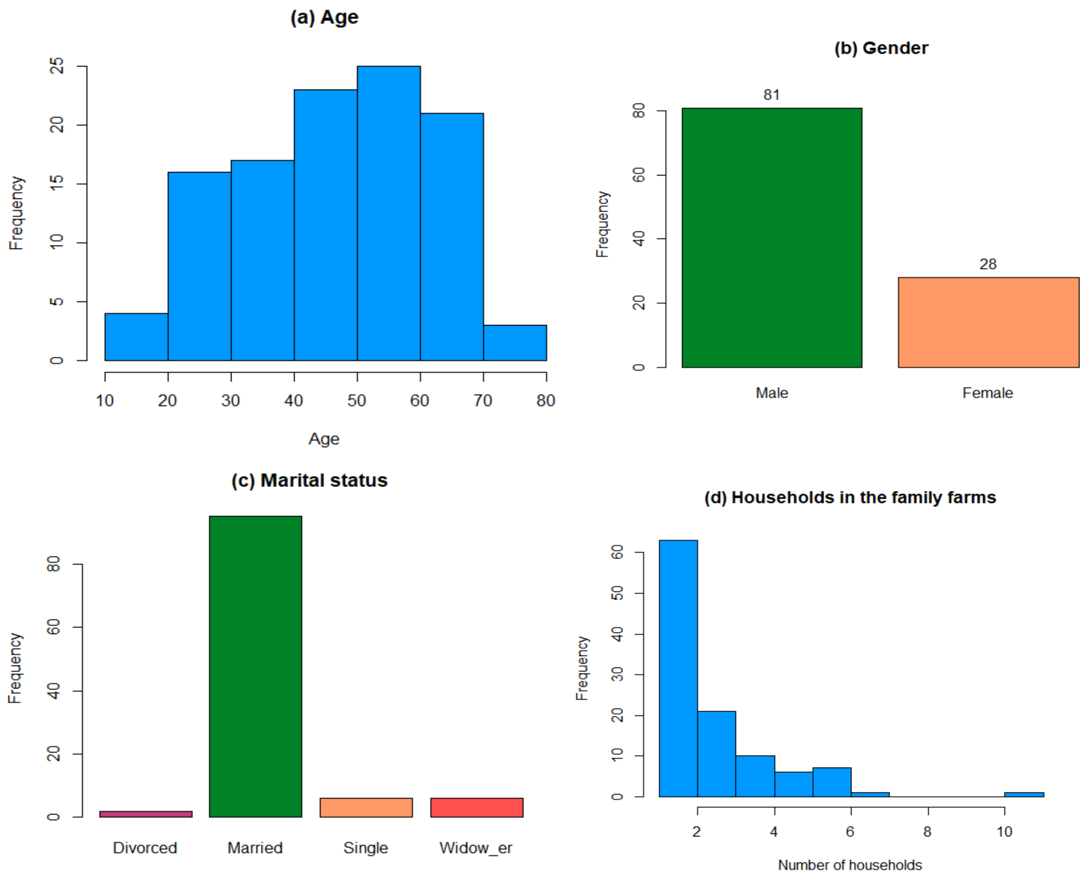

Figure 11: Aggregated distribution of age, gender, marital status, and household numbers of the family farms

Agriculture is the main source of income with 98.16% percent in all the study locations and the second source of income of the family farms member is animal husbandry (47.7%) across all the study locations (Fig.12a-b). Specifically, with regards to livestock availability, the family farms encompass an average of 2 cattle (Fig.12c). The number of goats, sheep and averaged 4, 3 respectively (Fig.12d-e).

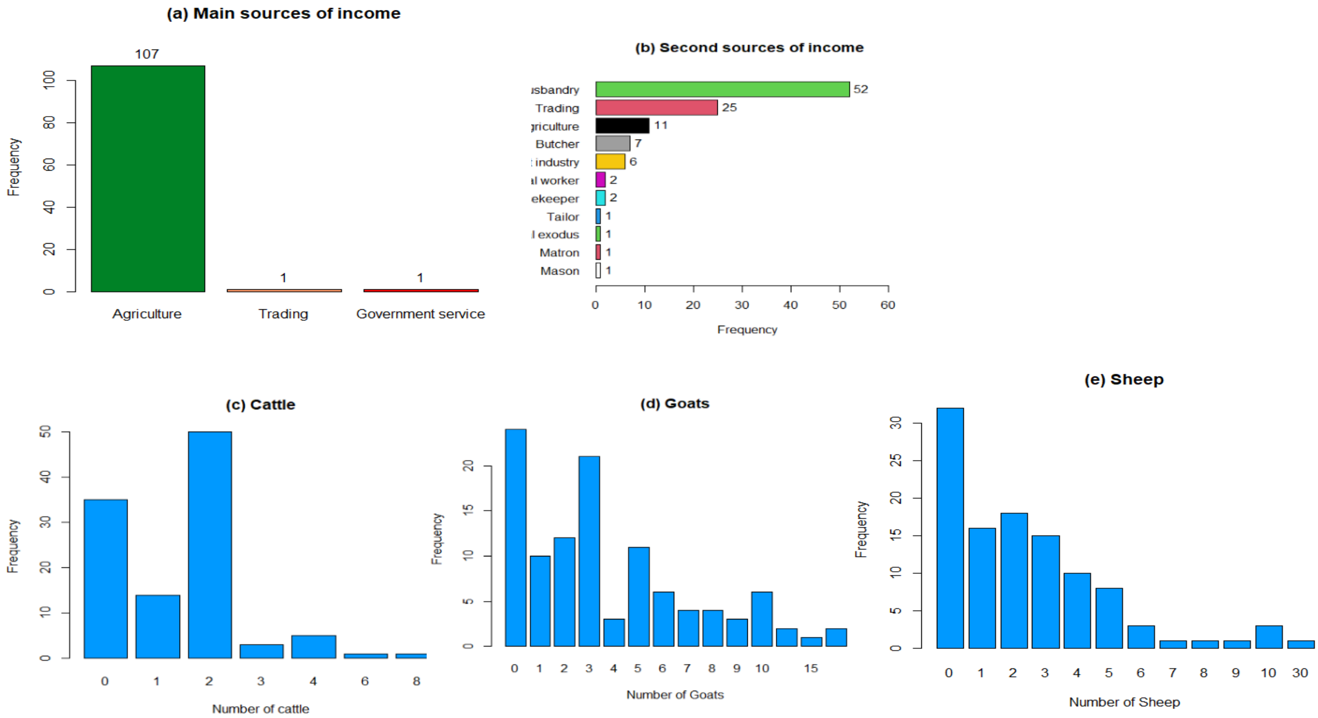

Figure 12: Main and second sources of income, and livestock availability in the family farms

It was observed that the family farms were very diverse in terms of crop species that farmers use for subsistence and to improve their revenue. Among the most crop species used are: millet (1), cowpea (1) followed by sorghum and other cash crops such as guinea sorrel, groundnut, peanut, and sesame (Fig.13).

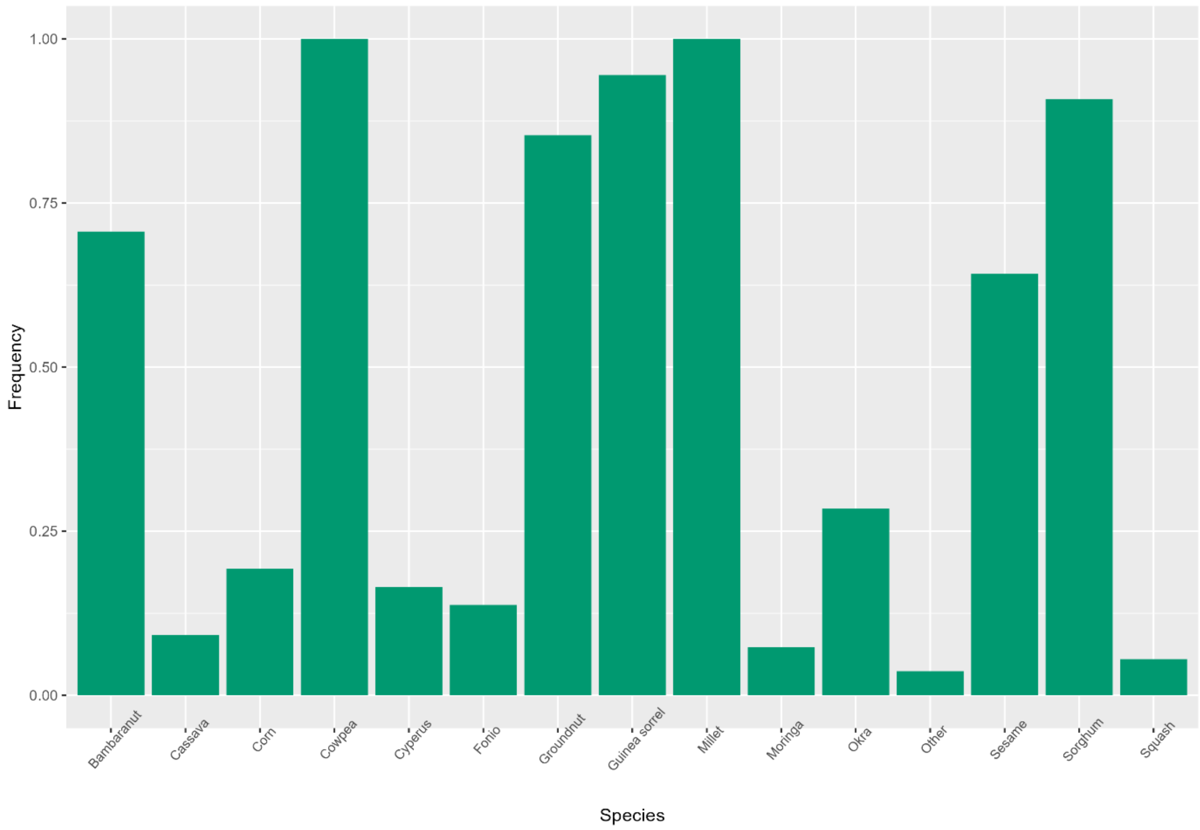

Figure 13: Crop diversity distribution in the family farms

The family farms are also characterized by the presence of the main field (MF) led by the head of the family farms as well as the presence of the fields led by the female (WF) with respectively 98.70% and 78.89%. (Fig.14a-b). In addition, smallholder farmers practiced mixed intercropping and diverse intercropping types were observed in WF (Fig.14a-b). Added to that, we observed that the soil of both of the field types is mainly fertile as indicated by farmers with 69 and 60 frequencies out of 107 respectively in the MF and the WF (Fig.14c-d).

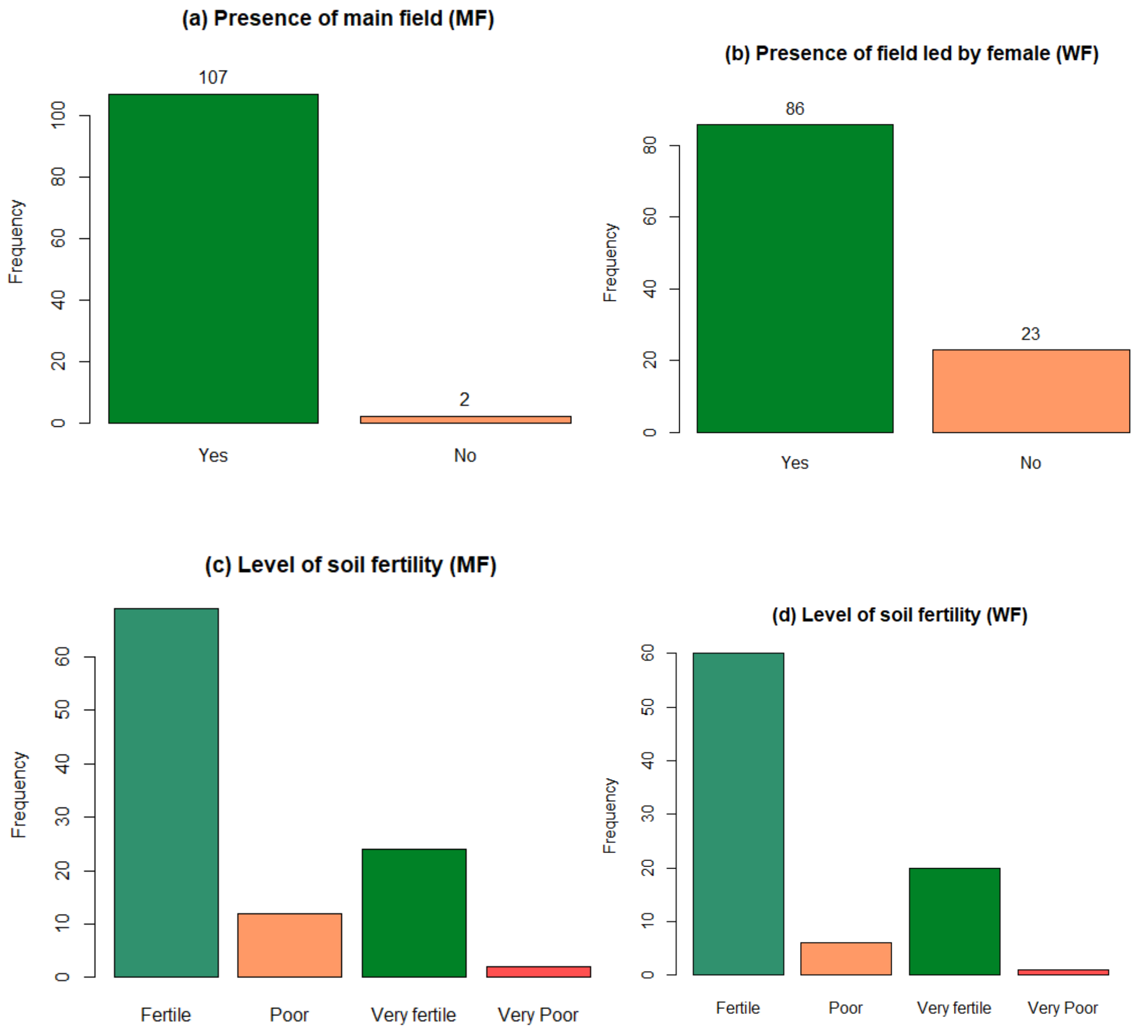

Figure 14: Presence of the main fields (MF) and the fields led by female (WF) and the soil fertility level in each of the field types

Moreover, the table 4 shows the Chi-square test between the gender and the presence of MF. From the table, the Pearson Chi-Square (p)=. 000.since $p<0.05$, it can be concluded that there was a statistically significant relationship between the gender (male) and the presence of the MF led by the head of the family farms.

Table 4: Relationship analysis between the presence of MF and gender with Chi-Square test

Main Field (MF)*Gender			
	Value	df	Asymp. Sig. (2sides)
Pearson Chi-Square	110.637[a]	4	.000
Likelihood ratio	11.943	4	.018
N of valid classes	110		

Legend: **a**. 7 cells (77.8%) have expected count less than 5. The minimum expected count is .01

Similarly, the table 5 showed that the Pearson Chi-Square (p)=. 000.since p<0.05, it could also be concluded that there was a statistically significant relationship between the gender (female) and the presence of the WF led by the women of the family farms.

Table 5: Relationship analysis between the presence of MF and gender with Chi-Square test

Field led by female (WF)*Gender			
	Value	df	Asymp. Sig. (2sides)
Pearson Chi-Square	114.450[a]	4	.000
Likelihood ratio	16.606	4	.002
N of valid classes	110		

Legend: **a**. 7 cells (55.6%) have expected count less than 5. The minimum expected count is .01

Further, fig.15a-b shows the size of the two fields within the family farm respectively the main fields and the fields led by the female of the family farms. The MF averaged a size of 3.0 ha and a minimum of 0.5 ha while the average size of the WF within the family farm was 1.5 ha with a minimum size of 0.5 ha.

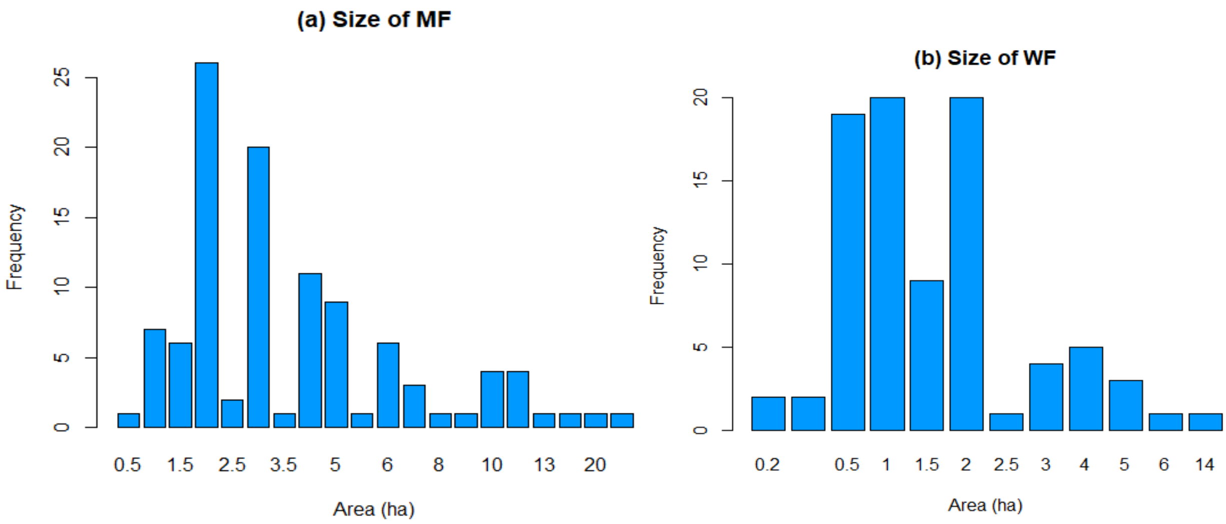

Figure 15: Distribution of the size of the two field types in the family farms

Fig.16a-d shows the yield distribution of the two main crops respectively in the MF and the WF.

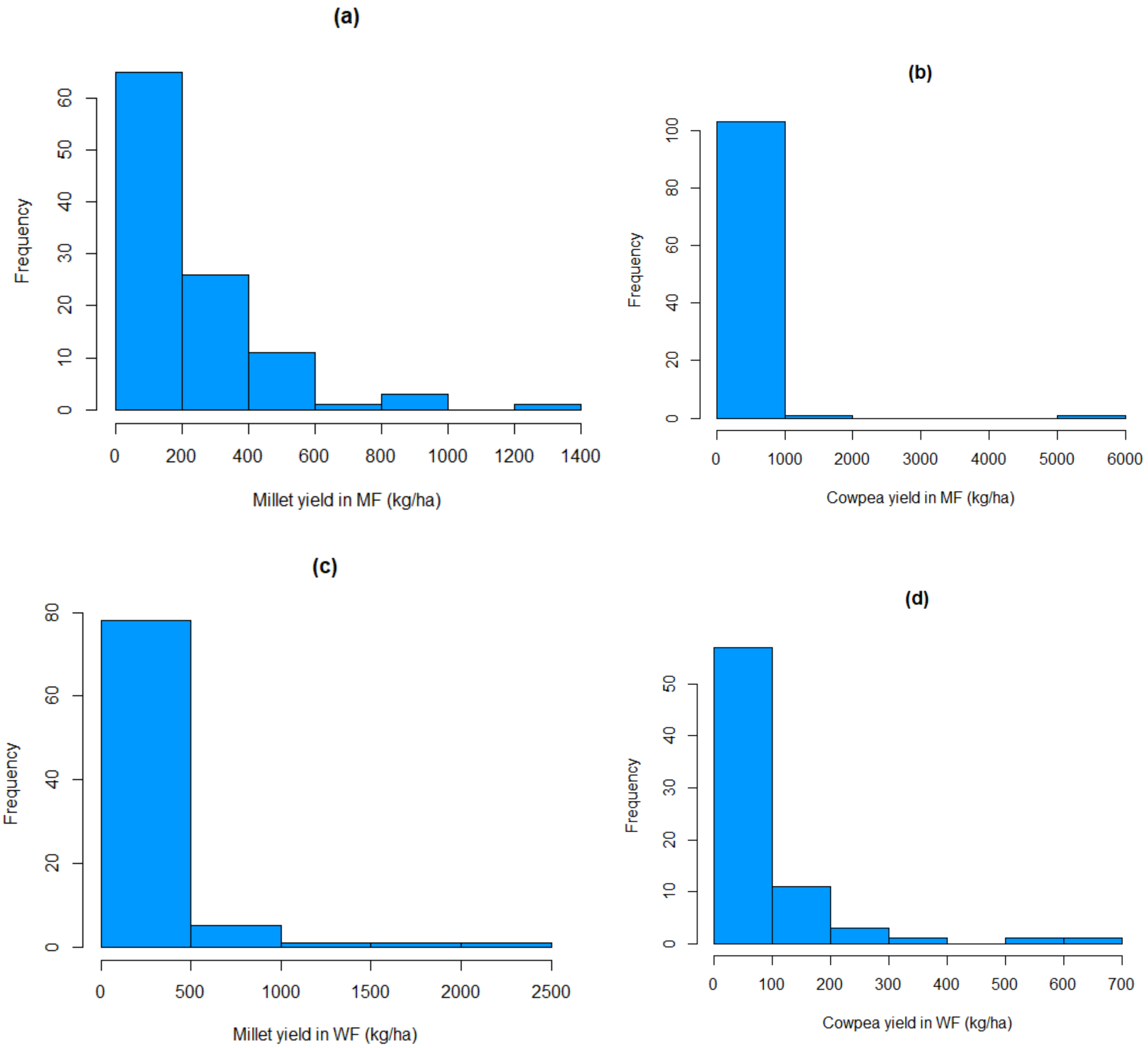

Figure 16: Millet and cowpea yields in the MF and the WF of the family farms

From the interaction with farmers, we observed that the millet yield averaged 209.58 kg/ha and 216.3 kg/ha respectively in the MF and the WF while the average of cowpea yield was 107.64 kg/ha and 77.38 kg/ha in the MF and WF respectively.

4.1.1.2. Key identified drivers hindering crop productivity in the family farms

The drivers that hinder the crop productivity were categorised into three (3) across the study locations: (i) soil constraints, (ii) rainfall uncertainties and (iii) socio-economic drivers.

Three main constraints related to soil were identified: wind erosion, water erosion and the soil fertility decrease.

Farmers mainly indicated the soil fertility decrease as the main soil constraints with the proportions of 61.1%, 76.5%, 88.2%, 90.0%, 95.0%, 95.2%, respectively for the villages of Karakara, Zebane Fiti, Kaboye Koira, Gade Iya, Saye Sabuwa, and Tchake (Table.6).

Table 6: Soil constraints as perceived by farmers in the different study locations

	Soil constraints (%)			
Village	Water erosion	Wind erosion	Soil leaching	Soil fertility decrease
GadeIya	40.0	20.0	10.0	90.0
Kaboye_Koira	0.0	11.8	5.9	88.2
Karakara	11.1	11.1	0.0	61.1
Saye_Saboua	10.0	15.0	15.0	95.0
Tchake	9.5	19.0	9.5	95.2
Zebane_Fiti	11.8	11.8	0.0	76.5

For the rainfall uncertainties, we identified 5 drivers: increase in the dry spells' frequency, increase in flooding frequency, late onset of the raining season, recurrent early cessation of the rainy season, and decrease in the rainfall amount. Among these, decrease in rainfall amount (10 to 55%) and the recurrent early cessation of the rainy season (20 to 70%) were considered by farmers as the main drivers impeding the crop production (Table.7).

Table 7: Rainfall uncertainties as perceived by farmers across the study locations

	Rainfall uncertainties (%)				
Village	Increase in dry spells frequency	Increase in flooding frequency	Late onset of the rainy season	Recurrent early cessation of the rainy season	Decrease in the rainfall amount
GadeIya	90.0	40.0	80.0	30.0	20.0
Kaboye_Koira	20.0	0.0	15.0	10.0	70.0
Karakara	16.7	11.1	5.6	55.6	27.8
Saye_Saboua	15.0	30.0	30.0	15.0	40.0
Tchake	14.3	23.8	23.8	47.6	57.1
Zebane_Fiti	20.0	0.0	20.0	35.0	60.0

Finally, the socio-economic drivers were categorized into 5: (a) farmers' low purchasing capacity, (b) demographic challenge, (c) crop residue exported from the fields, (d) farmers' inaccessibility to climate information, and (e) limited access to the market.

Table 8: Socio-economic drivers indicated by farmers across the study locations

	Socio-economic drivers (%)				
Village	Farmers' low purchasing capacity	Demographic challenge	Crop residue exported from the fields	Farmers' inaccessibility to climate info	Limited access to the market
GadeIya	33.3	22.2	11.1	22.2	44.4
Kaboye_Koira	0.0	0.0	8.3	16.7	66.7
Karakara	35.3	5.9	0.0	11.8	11.8
Saye_Saboua	80.0	20.0	30.0	0.0	10.0
Tchake	66.7	4.8	0.0	0.0	4.8
Zebane_Fiti	31.6	5.3	11.1	10.5	10.5

Among these, farmers' low purchasing capacity was the most socio-economic drivers (up to 88%) followed by the limited access to the near markets (10 to 66.7%) (Table.8).

4.1.1.3. Potential options for agroecological intensification explored in the family farms

In total, 12 potential options for AEI were identified across the study locations on each of the two fields' types.

In Gade Iya, farmers mainly practiced intercropping (60%), compost (60%) and organic manure (50%) in the main field (MF) while in the field led by female (WF), they mostly used intercropping (50%), compost (50%) and OGA ((40%) (a hygienic human urine used as organic fertilizer in Niger) (Fig.17a-b).

In Karakara (Fig.18a-b), the most potential AEI options used by farmers were the micro-dosing (83.3%) and the use of organic manure (50%) respectively for the MF and the WF.

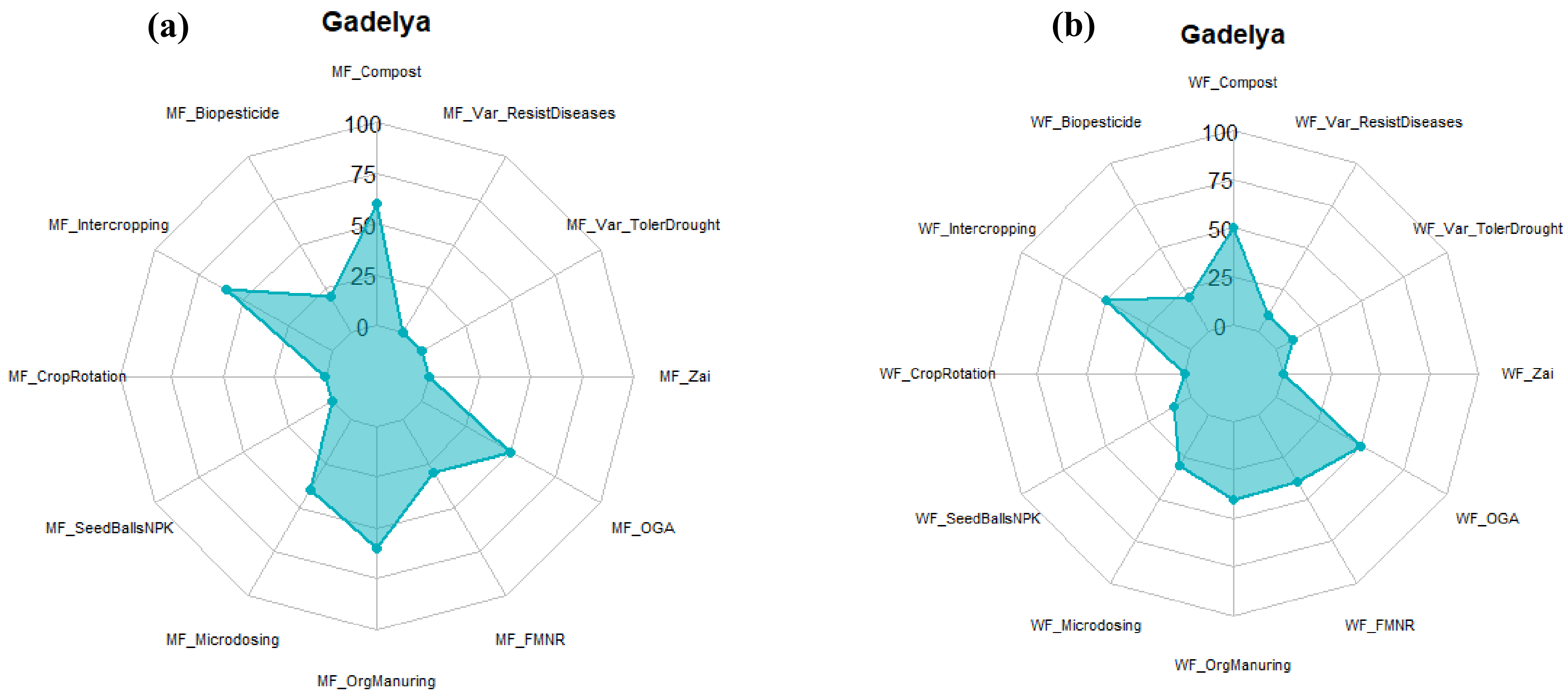

Figure 17: AEI options identified in the study location of Gade Iya

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms

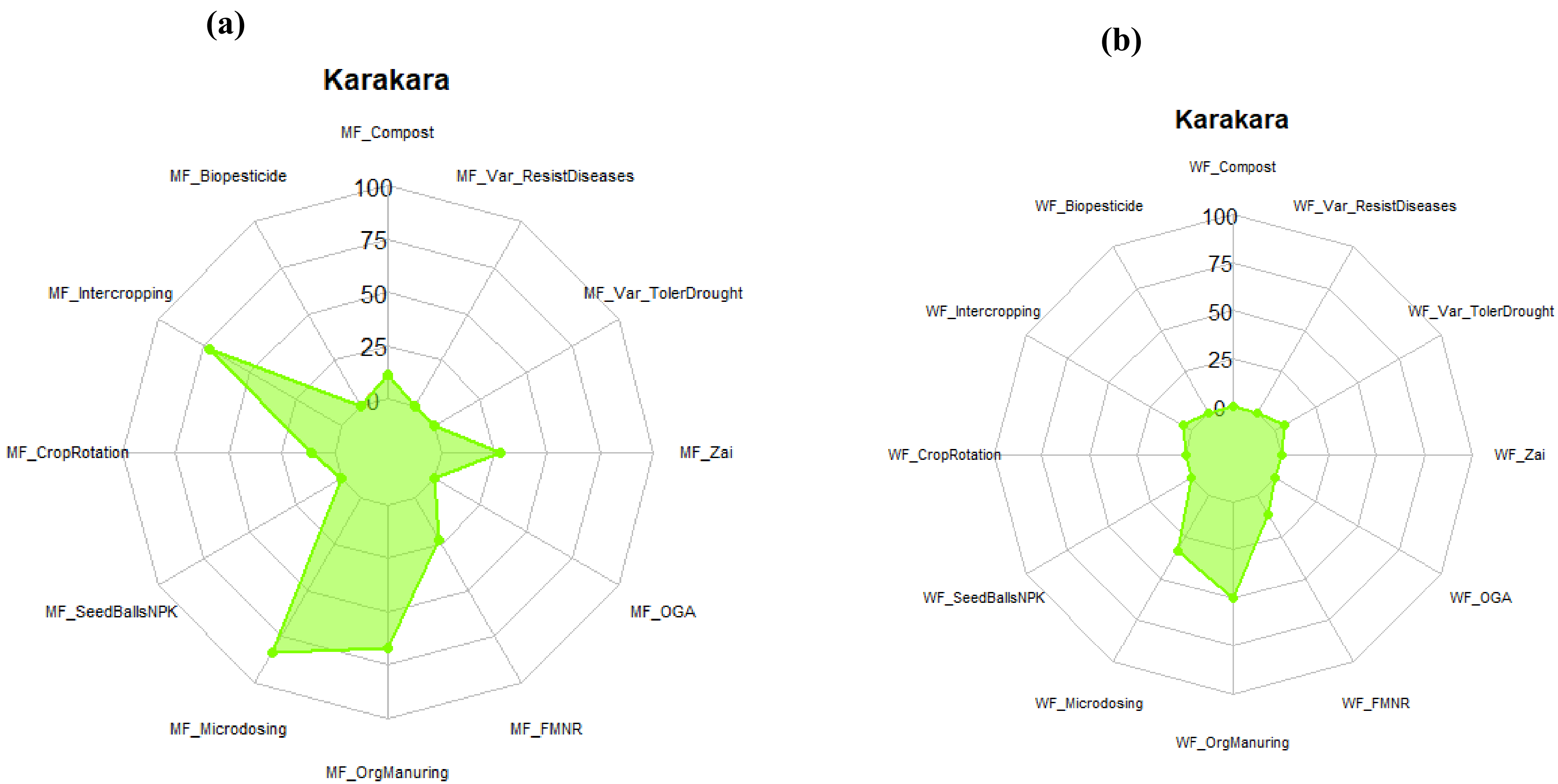

Figure 18: AEI options identified in the village of Karakra

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms

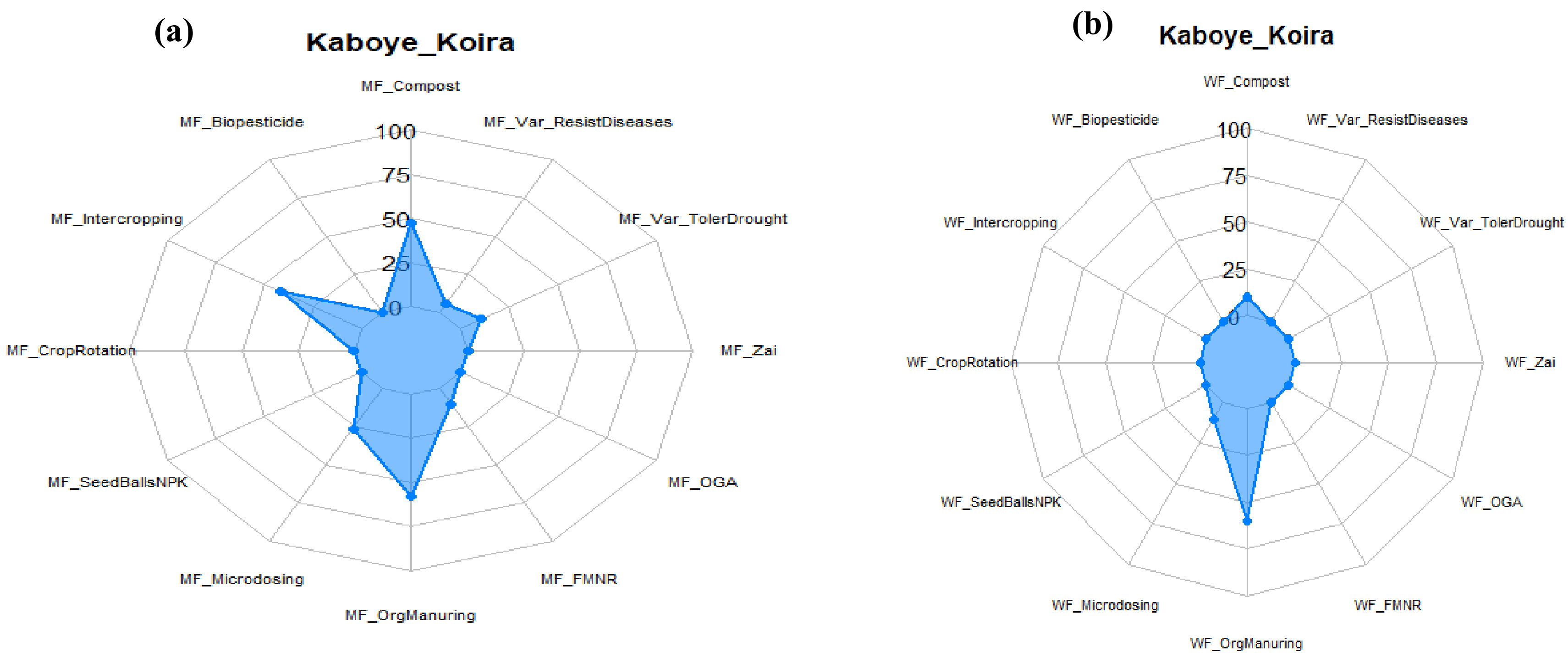

Figure 19: AEI options identified in the village of Koboye Koira

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms

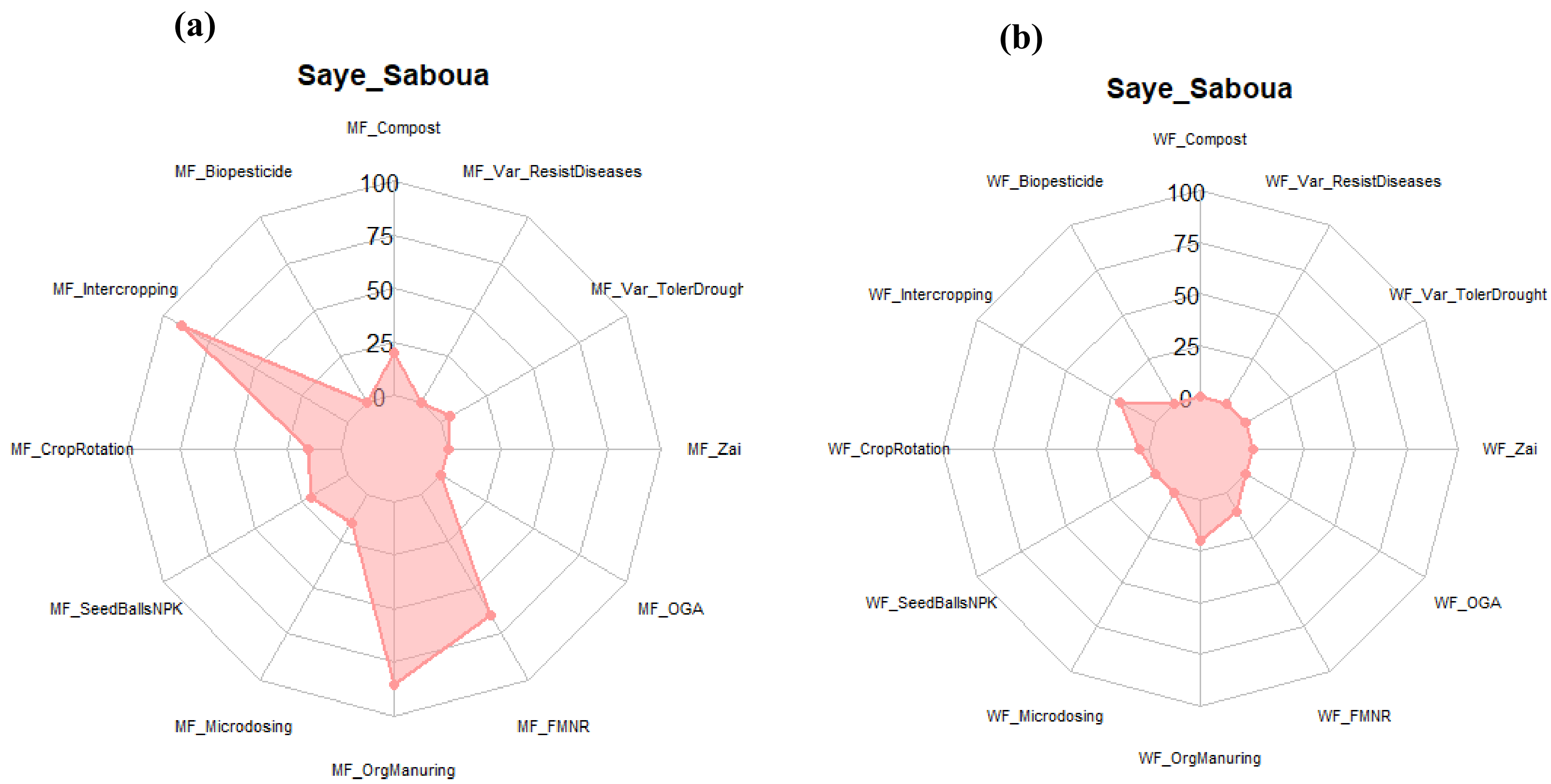

Figure 20: AEI options identified in the village of Saye Sabuwa

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms

(a)

(b)

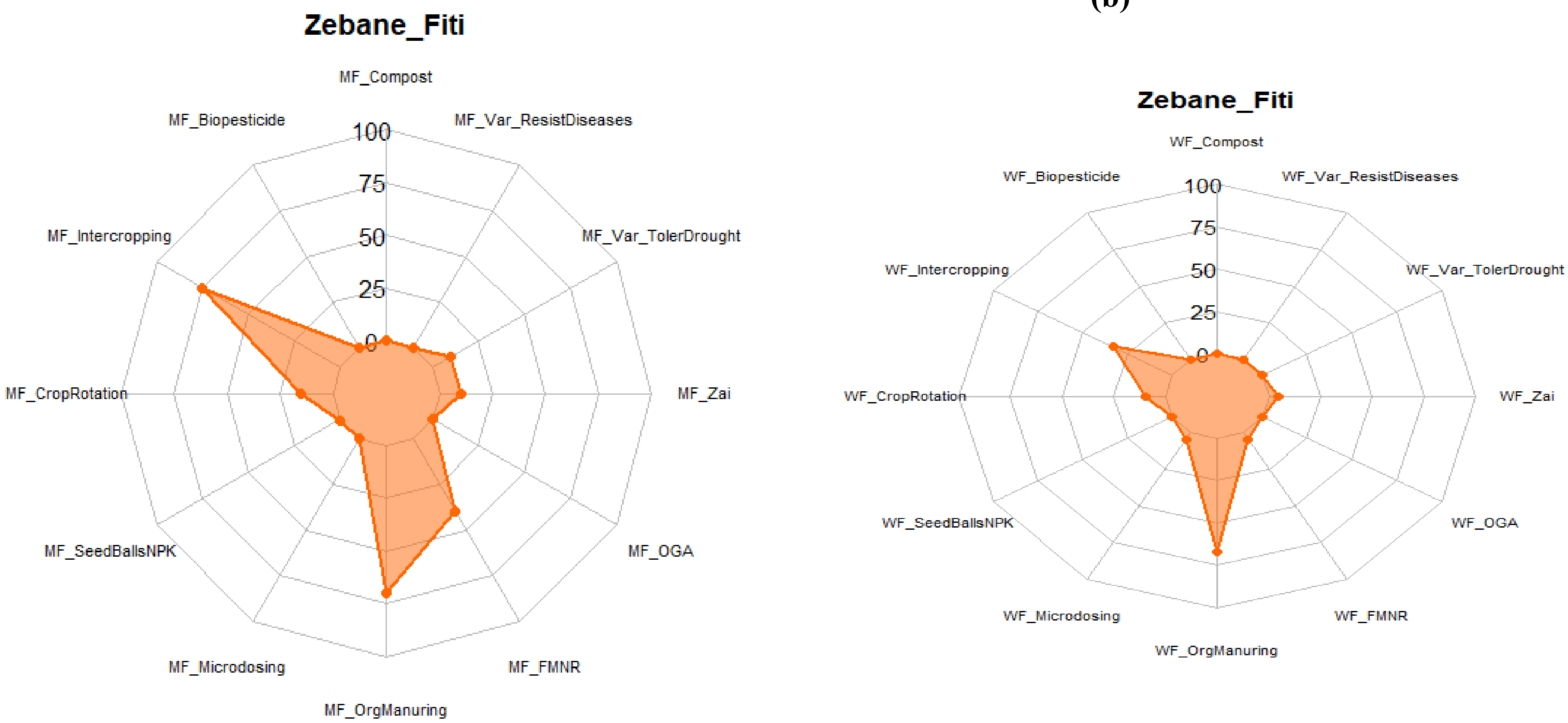

Figure 21: AEI options identified in the village of Zebane Fiti

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms

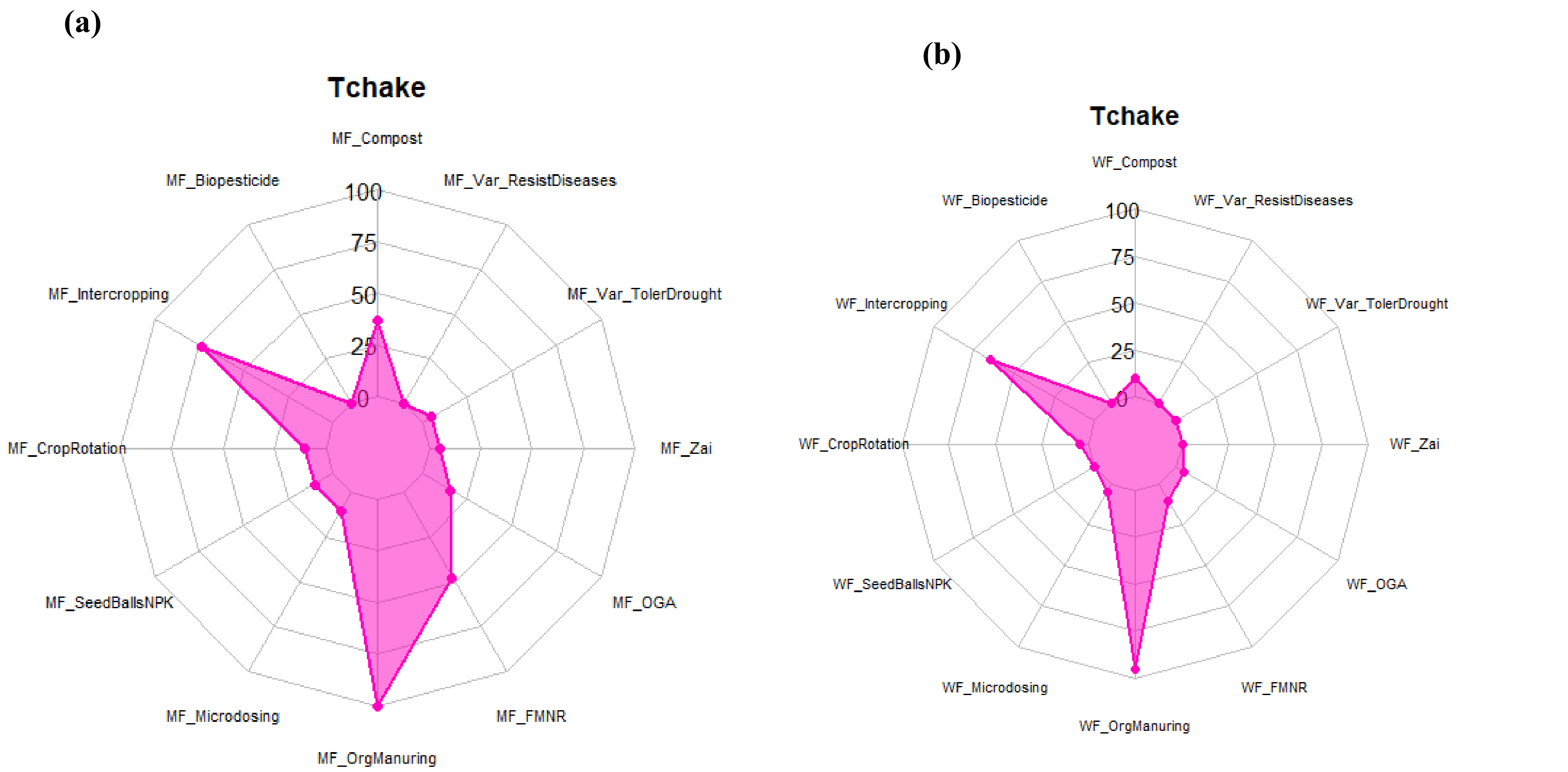

Figure 22: AEI options identified in the village of Tchake

Legend: (a) represents the main field (MF) and (b) the field led by the women (WF) in the family farms.

In the village of Kaboye Koira (Fig.19), organic manure was the most AEI options used by farmers in both the MF and WF with 57.9% and 60% respectively.

Whereas, in the village of Saye Saboua (Fig.20a-b) and Zebane Fiti (Fig.21a-b), intercropping was mainly practiced by farmers in the MF and the WF with 90% and 75% respectively and the organic manuring was the main AEI options practiced in Tchake (Fig 22a-b) with respectively.

Finally, the use of organic manuring was the most used AEI options in Tchake (Fig.22) in both the MF and WF with 100% and 95% respectively.

Overall, the main AEI options practiced in the small family farms across the study locations in both of the field’s types were: the intercropping of cereal-legume, the organic manuring application, the mineral fertilizer technique, the FMNR (farmer managed natural resources) as well as the use of compost.

Fig.23 highlights that the main source of income in the family farms remains agriculture.

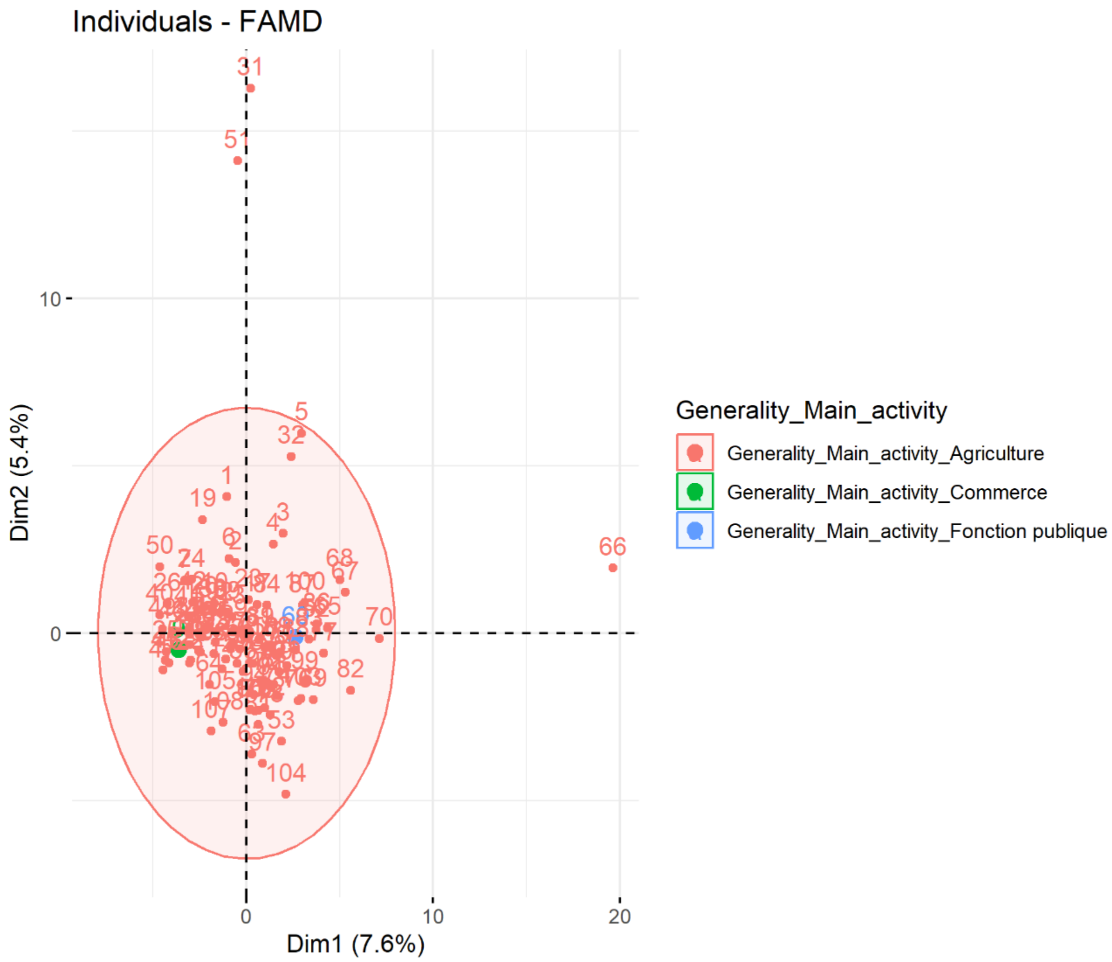

Figure 23: FAMD highlighting the main source of income in the family farms

Figure 24 shows that women are actively involved in the agricultural tasks in the family farms in spite the fact that less than 30% of the surveyed farmers across the family farms were female.

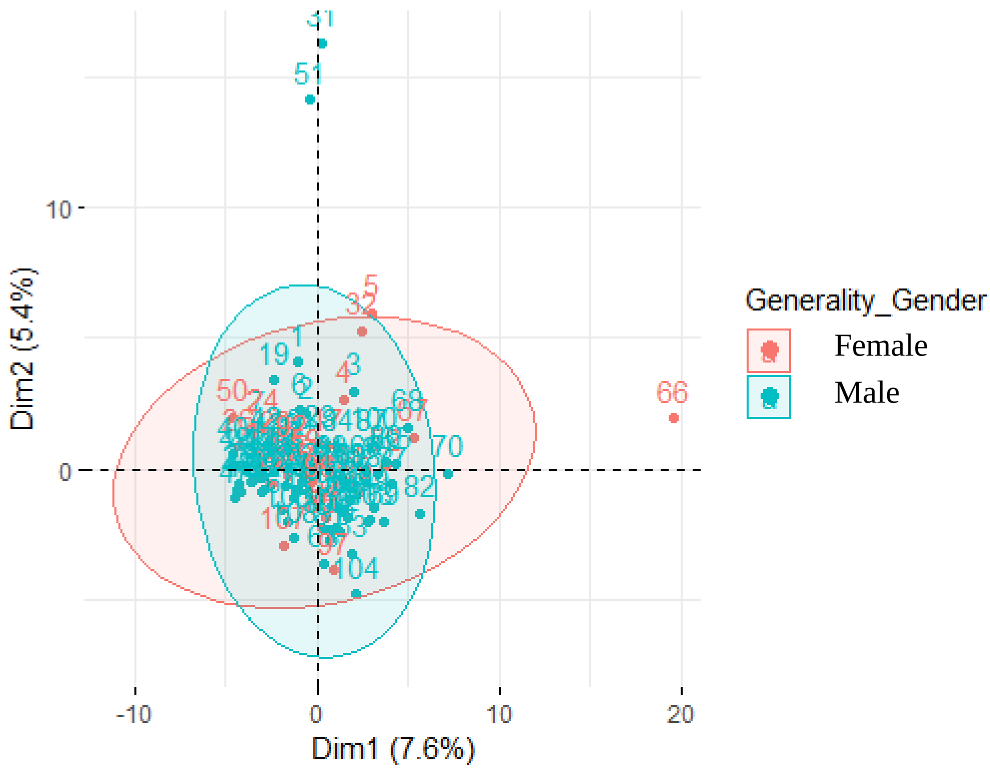

Figure 24: FAMD highlighting the importance of gender in the family farms

Furthermore, having aggregated the main variables characterizing the family farms, figure.25 revealed that there exists a strong relationship among all the villages with respect to resources endowment, constraints and opportunities.

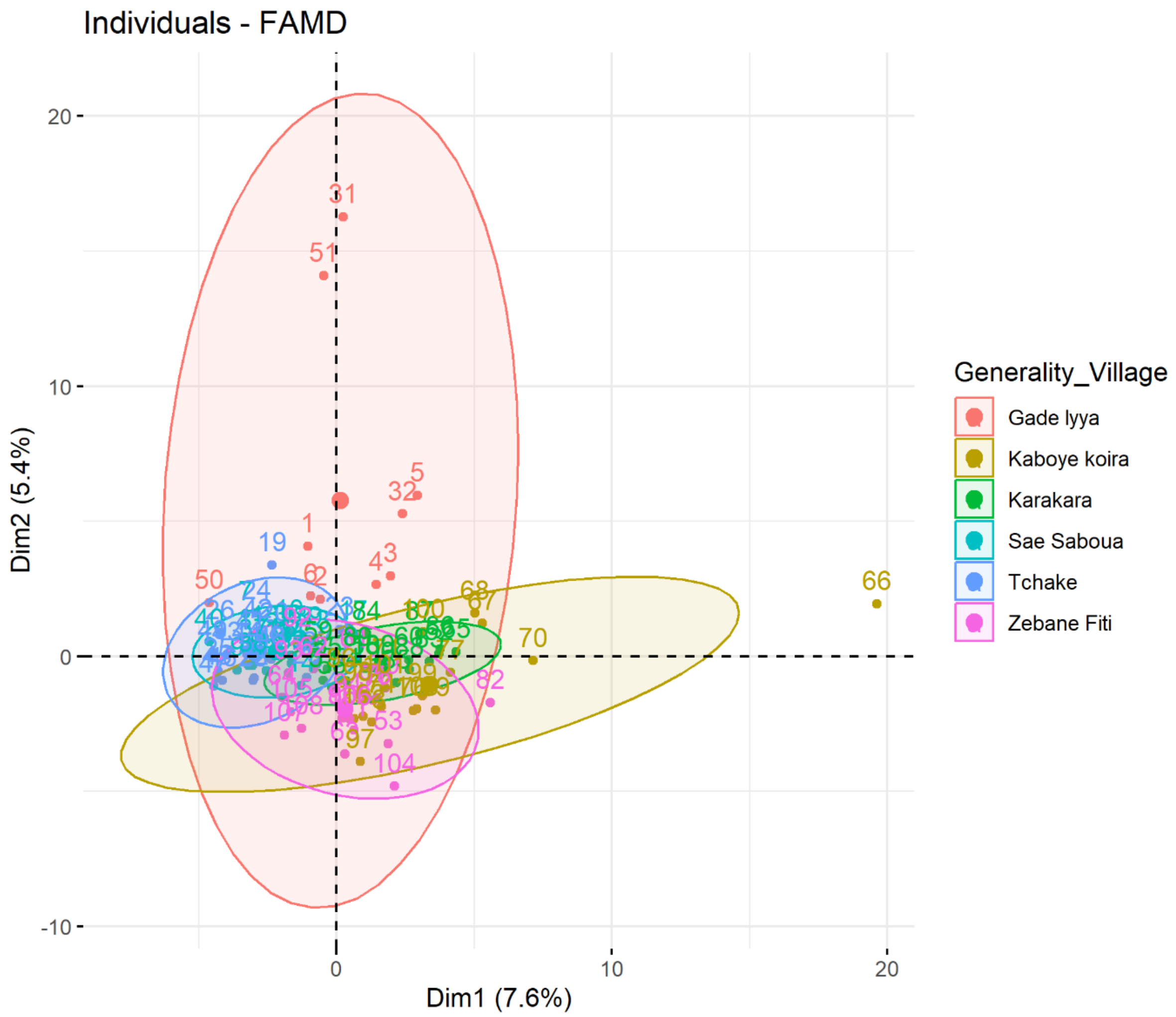

Figure 25: FAMD showing the relationship between the selected study locations for family farm characterization

This is obvious as the farmers' federations assisted with their records in selecting the villages with common features: the possible and the close farm characteristics, the close resources, and the same AEI options. However, little differences were observed in the village of Kaboye Koira and Gade Iya which could be explained by the steady progress of the farmers in adopting new technologies and the presence of many projects' interventions in these two villages apart from the CowpeaSquare project. Moreover, it could be due to the belonging to different farmer organisation as the choice are independent.

Regarding the key drivers hindering crop productivity in the family farms, it was observed that the soil fertility decline was the most significant constraint among the villages.

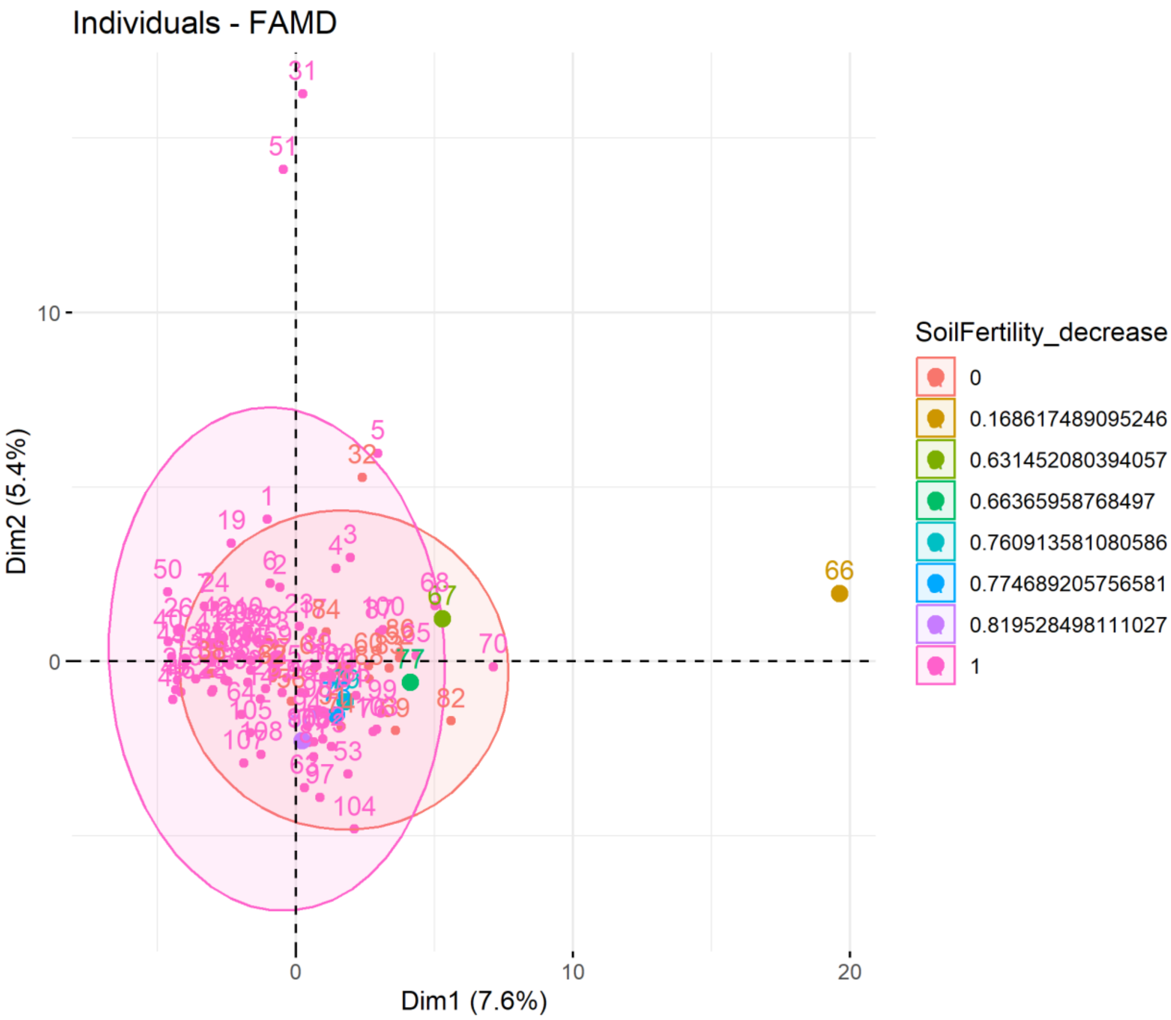

Figure 26: Distributed FAMD showing soil fertility decline as the significant key driver in the family farm context

4.1.2. Part II: Co-building an integrative and transdisciplinary trial design for the implementation of agroecological options in the context of local family farms: A pilot methodological experiment in Niger

This part II presents consecutively the results of the specific objectives two and three of the study.

4.1.2.1. Serie of steps developed during the co-design process of the integrative trial

Figure 27 shows the steps developed when co-designing the integrative trial.

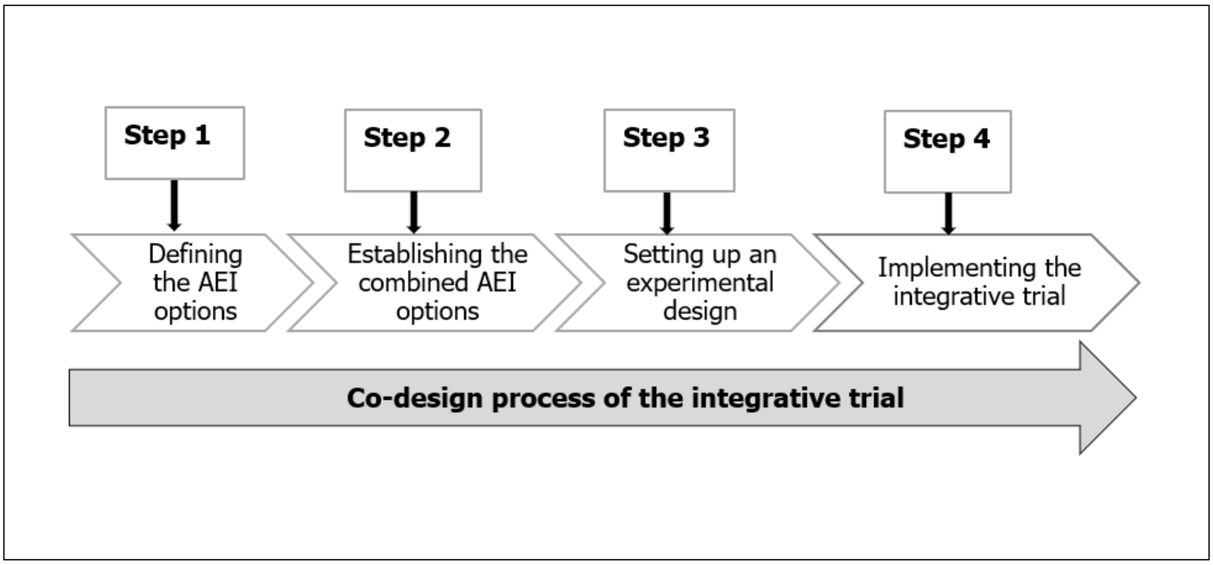

Figure 27: Serie of steps developed for co-designing the integrative trial of the combined AEI options

- **Step 1: Defining the AE options**

It represents the definition of the AE options based on the real problems that hinder the smallholder farming systems of Niger. This step consists of exploring collectively the AEI options based on the shared individual experiences of the projects and the involved organisations. The AEI options were defined through a workshop held at the RECA (Reseau des Chambres d'Agriculture du Niger) in Niamey in April 2021. The workshop gathered multi-stakeholders and interdisciplinary teams that were involved in different projects dealing with one or more agroecological principles. Many institutions such as Mooriben, Fuma Gaskiya, UDDM, CIRAD, IRD, UAM, and INRAN participated in the workshop. During the workshop, (i) a brainwriting technique was used to generate a set of AEI options which represent potential solutions from individual participants depending on their specific expertise. (ii) The participants then regrouped to evaluate and discuss the AEI options being brain written by classifying them into three main categories of thematic areas i.e., Cropping system (CS), Soil fertility management (SM) and Varietal diversity (VD). (iii) Two AEI options (Table.9) were selected within the basket of options as a priority by each thematic area through discussion and arbitration.

Table 9: The selected AEI options per thematic areas during the workshop on co-designing the integrative trial

	Thematic areas		
AEI options	CS options	SFM options	Cowpea varietal diversity
AEI option 1	Millet-cowpea intercropping (MC-intercrop)	DecomposedOrganic manure (OrgM)	CS039
AEI option 2	Cowpea sole cropping (CSC)	DAP micro-dosing (DAP_m)	CS126

- **Step 2: Establishing the combined AEI options**

Based on the selected AEI options from step 1, participants reintegrated their empirical project experiences to define all the combined AEI options systematically. This resulted in the identification of eight (8) combinations (2 x 2 x 2) of AEI options which represent the statistical treatments to be implemented in the unit plots of the experiment (Table.10).

Table 10: Combined AEI options established in the co-design process of the integrative trial

Codes of combined AEI options	Description of combined AEI options
A1	Organic manure × MC-intercrop × CS039
A2	Organic manure × CSC × CS039
A3	Organic manure × MC-intercrop × CS126
A4	Organic manure × CSC × CS126
B1	DAP micro-dosing × MC-intercrop × CS126
B2	DAP micro-dosing × CSC × CS126
B3	DAP micro-dosing × MC-intercrop × CS039
B4	DAP micro-dosing × CSC × CS039

- **Step 3: Setting up a statistical experiment of the integrative trial**

A multi-factorial experimental design that integrated 2 levels was set up:

A main plot (level 1), whose plots were constituted based on the soil fertility management (SFM) treatment, with as modality 1 "application of 100g of decomposed mixed manure per seed hole" and as modality 2 "the fertilizer micro-dosing application of 2g DAP per seed hole".

A secondary plot (level 2) plot with modalities corresponding to the 4 combinations of the cropping systems (CS) factor (modalities: millet-cowpea intercropping versus 100% cowpea sole cropping) with the cowpea varietal diversity factor (2 modalities: variety 1 and variety 2) without replication per site. But all four sites were considered as replicates in the statistical analyses.

- **Step 4: Implementation of the integrative trial by supporting & documenting the adaptation to local constraints without undermining the experimental design**

Before implementing the integrative trial, a focus group discussion was conducted with farmers and technicians to agree on the details of the implementation of technical itineraries (sowing methods, ploughing methods, crop management practices). All the agreed adjustments and precisions in the implementation of the integrative trial were documented to support the interpretation of the findings.

4.1.2.2. Rainfall distribution

The 2021 season started earlier in the Centre-south (Gwassalle and Saye Sabuwa) than in the Western part (Garke and Kaboye Koira). The total rainfall (427.5; 513.5; 405.6 and 541.7 mm) (Fig.28) respectively in Garke, Gwassalle, Kaboye Koira; and Saye Sabuwa was below the long-term average of the districts of Falwel (500 mm) and Saye Sabuwa (614.6 mm).

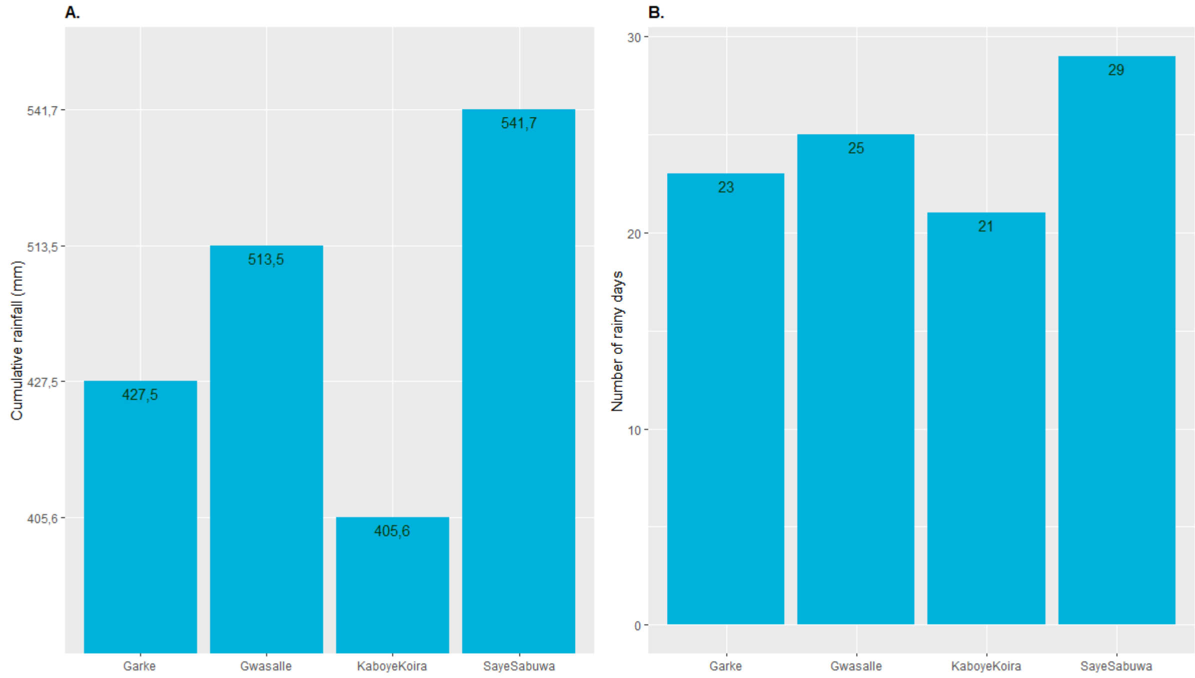

Figure 28: Rainfall distribution of the four pilot sites of the integrative trial

Legend: A represents the cumulative rainfall and **B** represents the number of the rainy days in the study locations.

The Centre-south (Gwasalle and SayeSabuwa) received more rainfall than the Western part (Kaboye Koira and Garke) of Niger. This season was characterised by a series of dry spells which affected crop performance across the study locations specifically in the study locations of Kaboye Koira and Garke. Rains stopped prematurely at the beginning of October.

4.1.2.3. Effect of participatory assessment on combined AEI options

The multi-criteria index (IVM) was used to evaluate farmers' preferences for the most promising combined AEI options. Some equations were applied to compute it. The overall formula was described in the methodology.

A1, A2, A3 and A4 are the most preferred combined AEI options depending on the pilot sites.

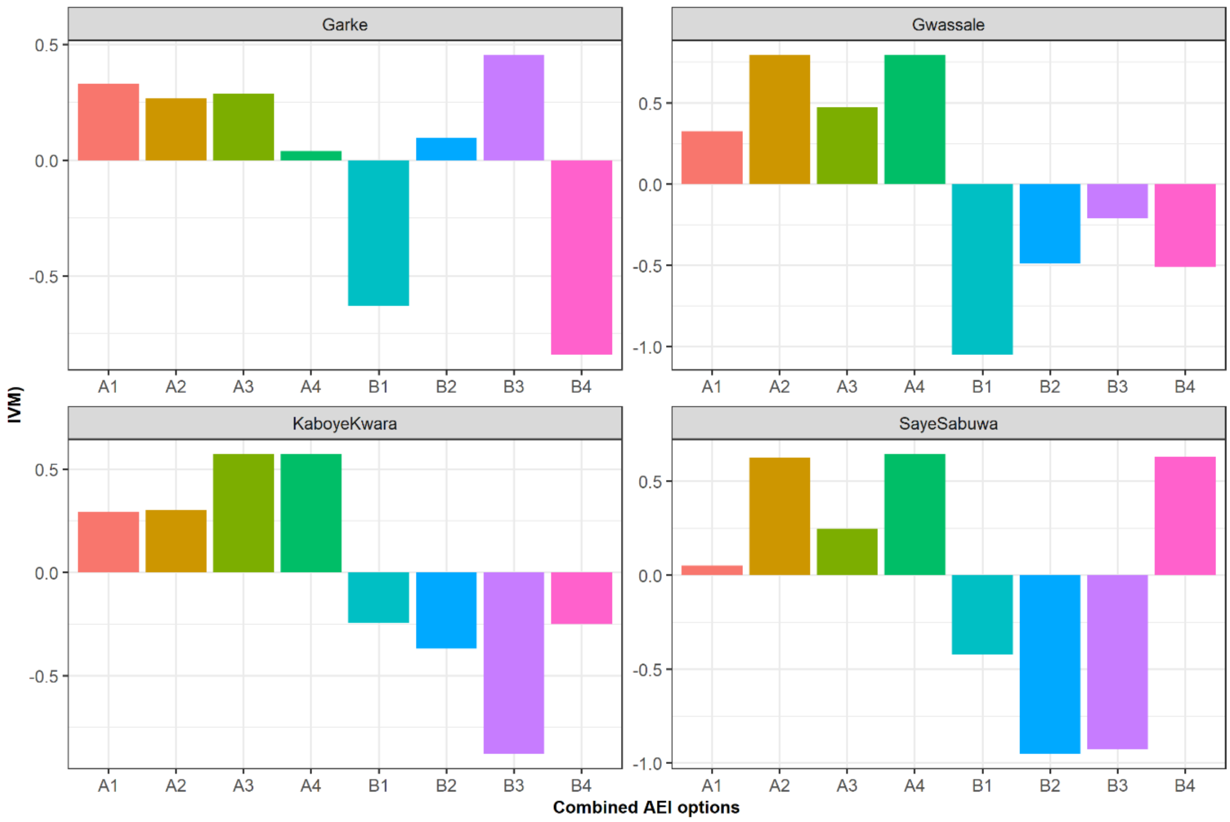

Figure 29: Farmers 'assessment of the performance of the combined AEI options across the four pilot sites

In the Centre-South of Niger i.e., in Gwassalé and Saye Sabuwa, A2 and A4 were the best combined AEI options selected by farmers. These A2 and A4 recorded respectively 0.62 and 0.64 in Saye Sabuwa while an equal IVM of 0.8 was obtained in the study of Gwassale. In Garke (i.e., the Western part of Niger), A1(IVM=0.33) and B3 (IVM=0.45) (Fig.29) were the most preferred combined AEI options by farmers respectively.

4.1.2.4. Effects of individual AEI options on crop yield components

The integrative design allowed the test of the effect of combined options together, as a "whole plot" effect. However, the methodology allowed also the analysis of individual options effects.

A large variability of grain and haulm yields and DPI was found across the four study locations:

Grain yield varied from a median of 22 to 150 kg. ha-1 and from a median of 24 to 197 kg. ha-1 respectively for the CS039 and CS126 cowpea varieties in Gwassale (Fig.30a). Whereas, in Kaboye Koira and Garke, there is larger variability of grain yield for the two varieties despite the low grain yield being recorded. Haulm yields and DPI of the two varieties did not vary in all four study locations (Fig.30b-c).

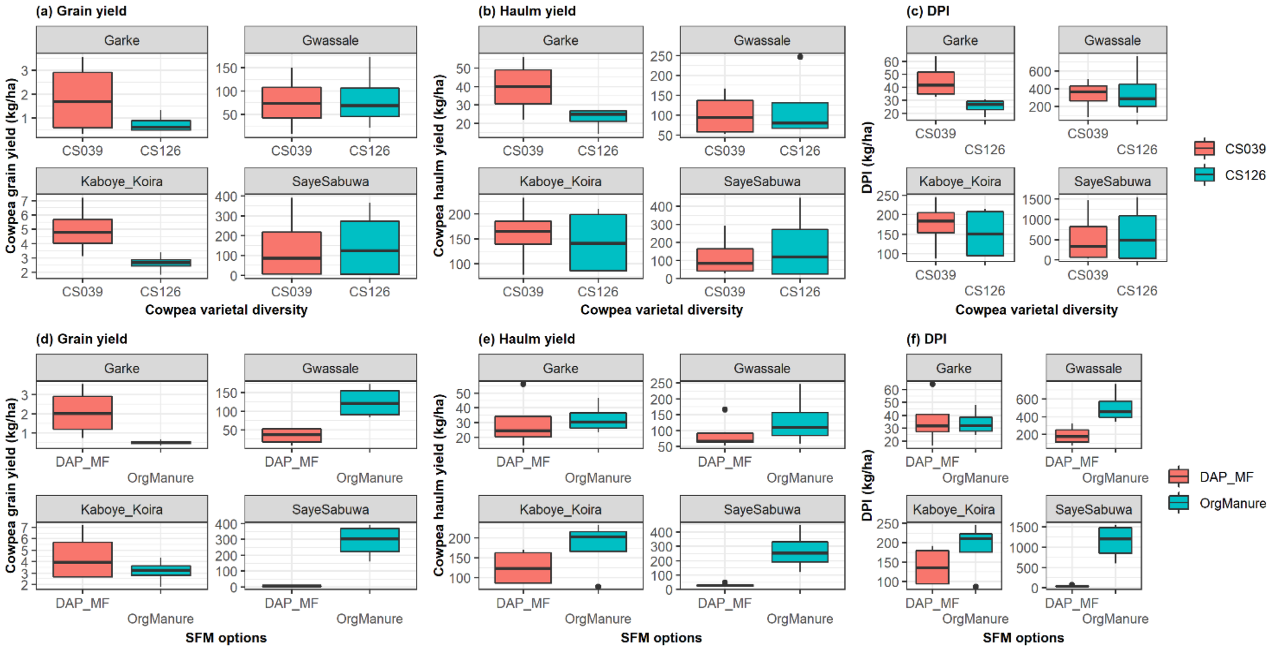

Figure 30: Grain and haulm yields, and DPI for the cowpea varietal diversity (CDV) options and the soil fertility management (SFM) options over the four pilot sites

Legend: **(a), (b), (c)** are the yield components for the cowpea varietal diversity option, and **(d), (e), (f)** for the SFM the options.

There is no significant difference in grain or haulm yields between the two varieties (Fig.30a-c and Table.11).

Further, a wider variability concerning SFM options was also observed. In the study location of Gwassale, cowpea grain yield ranged from a median of 22 to 50 kg. ha^{-1} and 100 to 152 kg. ha^{-1} respectively for the treatments of the decomposed organic manure and the DAP fertilizer as micro-dosing.

Table 11: Summary of the output of the ANOVA showing the effects of individual AEI options

Source	DF	F-value	P-Value
(a) Cowpea grain yield (kg. ha^{-1})			
Village	3	5.83	**0.004**
CDV	1	0.02	0.883
SFM options	1	10.38	**0.004**
CS options	1	1.05	0.315
CDV × SFM options	1	0.02	0.885
CDV × CS options	1	0.001	0.967
SFM options× CS options	1	0.42	0.523
CDV× SFM options × CS options	1	0.016	0.90
(b) Haulm yield (kg. ha^{-1})	DF	F-value	P-Value
Village	3	4.51	**0.013**
CDV	1	0.13	0.715
SFM options	1	10.18	**0.004**
CS options	1	4.18	0.053
CDV × SFM options	1	3.35	0.0814
CDV × CS options	1	0.07	0.789
SFM options× CS options	1	2.22	0.15
CDV× SFM options × CS options	1	0.04	0.835
(c) DPI of cowpea varieties (kg. ha^{-1})	DF	F-value	P-Value
Village		4.87	**0.009**
CDV		0.04	0.837
SFM options		11.05	**0.003**
CS options		1.71	0.204
CDV × SFM options		0.31	0.582
CDV × CS options		0.001	0.974
SFM options× CS options		0.76	0.391
CDV× SFM options × CS options		0.022	0.881

Legend: Significant effects per yield component are shown in bold in the column of P-value. CDV means Cowpea varietal diversity; SFM: Soil fertility management and CS: Cropping Systems

The use of the decomposed organic manure significantly increased grain and haulm yields ($P < 0.01$) (Fig.30d-f and Table.11) compared to the application of 3g of DAP.

Nevertheless, the use of DAP micro-dosing increased grain yield and haulm yield in the study locations of Garké and Kaboye Koira (Fig.30d-f and Fig.31d-f). There were no significant interactions (Cowpea variety × SFM options) at ($P< 0.05$) but the interactions are slightly different ($P=0.08$).

For the CS options, similar variability was observed since the two varieties performed well depending on the study locations (Fig.31a-c). The haulm yield showed a significant difference (P< 0.05) (Table.11) between the cowpea sole cropping and the millet-cowpea intercropping.

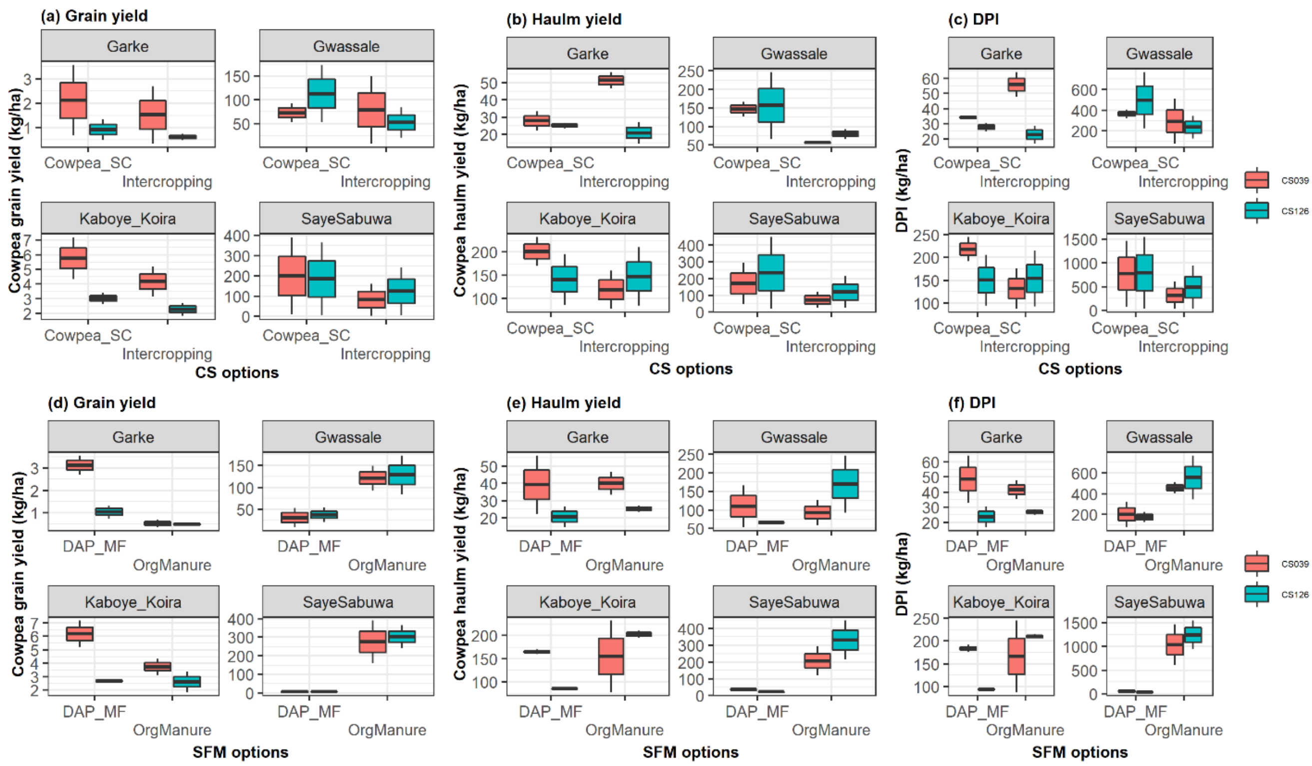

Figure 31: Grain and haulm yields and DPI of cowpea varieties for the cropping system (CS) options and the SFM options effect per cowpea variety over the study locations.

Legend: **(a), (b), (c)** represent the yield components for the CS options and **(d), (e), (f)** for the SFM options.

The integrative analysis of the four study locations showed that the two cowpea varieties performed well both in the sole cropping and the intercropping as well as with the use of the two different SFM options (Fig.30a-c and Fig.31a-f). However, there is no significant difference (P< 0.05) between the two varieties and with the interactions (i.e., Cowpea variety × SFM options, Cowpea variety × CS options) (Table.11).

The linear mixed-effects models (Allan & Rowlands, 2001) were used to check the most significant combined AEI options.

Table 12: Summary of the output of the generalized linear mixed model (GLMM) showing the effects of the combined AEI options

(a) Cowpea grain yield (kg. ha^{-1})					
Combined AEI options	Est.	S.E.	T-value	DF	P-value
(Intercept)	78.50	51.78	1.52	12.04	0.16
A2	43.60	57.81	0.75	21	0.46
A3	3.64	57.81	0.06	21	0.95
A4	56.95	57.81	0.99	21	0.34
B1	-71.27	57.81	-1.23	21	0.23
B2	-62.80	57.81	-1.09	21	0.29
B3	-73.83	57.81	-1.28	21	0.22
B4	-60.43	57.81	-1.05	21	0.31
(b) Cowpea haulm yield (kg. ha^{-1})					
Combined AEI options	Est.	S.E.	T-value	DF	P-value
(Intercept)	76.11	44.94	1.69	14.52	0.11
A2	95.28	52.96	1.80	21	**0.09**
A3	59.86	52.96	1.13	21	0.27
A4	151.94	52.96	2.87	21	**0.01**
B1	-28.06	52.96	-0.53	21	0.60
B2	-26.11	52.96	-0.49	21	0.63
B3	-2.08	52.96	-0.04	21	0.97
B4	25.28	52.96	0.48	21	0.64

Legend: Significant effects per yield component are shown in bold in the column of P-value.

Out of the eight combined AEI options tested in four study locations, two (A2 and A4) have shown significant differences: A2 at ($P<0.05$) and A4 at ($P<0.01$) (Table.12) with respect to haulm yield.

4.1.3. Part III: Performance of cowpea genotypes selected through participatory varietal selection and participatory breeding under different local contexts of the smallholder farmers in Niger

This part III presents the results of the specific objective four of the study.

4.1.3.1. Rainfall distribution across the study locations

Figure 32 shows the cumulative rainfall and the number of rainy days across the study locations of the decentralized trials. It was evident that the 2022 rainy season was a year with normal rainfall trend. The village of SarkingBindiga (SSB) recorded the highest cumulative and number of rainy days which was not surprised because it is located to one of the rainiest areas i.e., the Savannah zone of Niger. However, it was observed that some villages received higher cumulative rainfall in less than 30 days of rain and lower cumulative rainfall in more than 30 rainy days. This means that regardless of the high cumulative rainfall, dry spells occurred in some of the study locations such as ZFT, BRK, KRK, MYR, DAM and BSG.

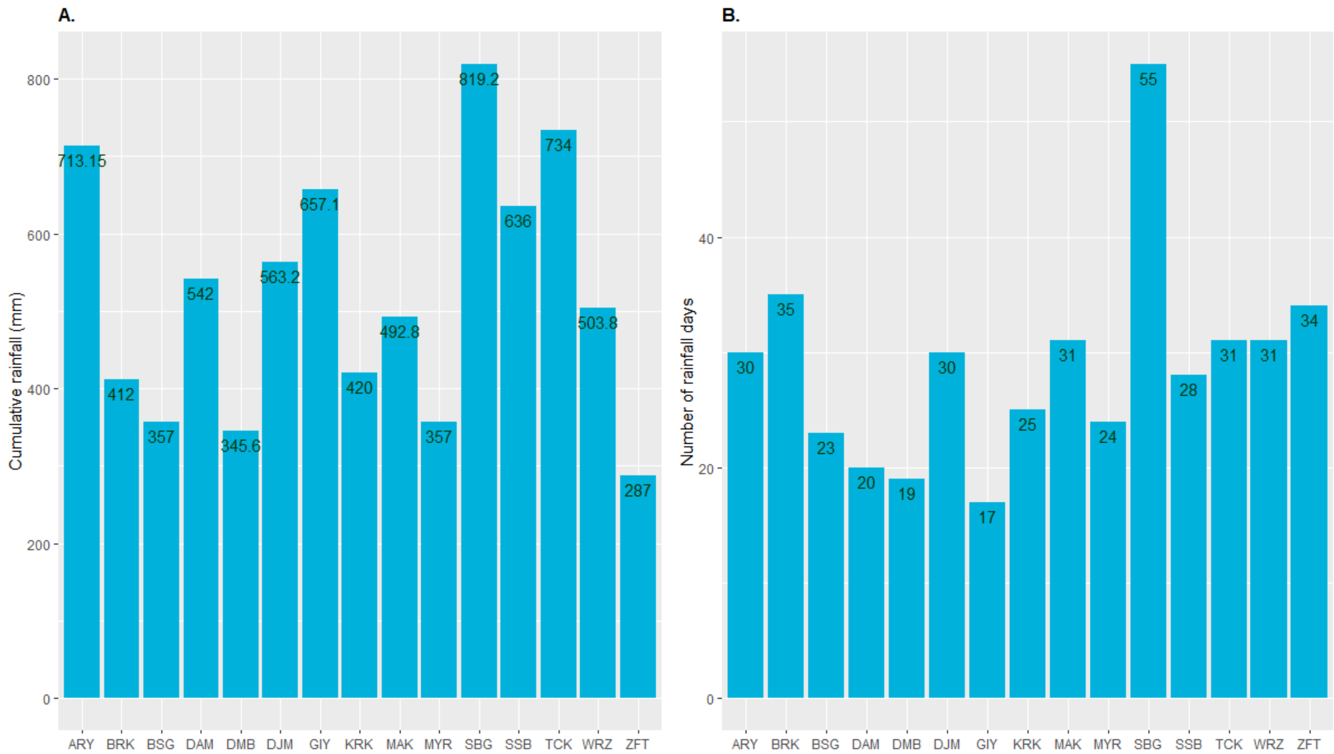

Figure 32: Cumulative rainfall and number of rainy days across the selected fifteen study locations for the decentralised trials of cowpea

Legend: A: Cumulative rainfall. **B:** Number of rainy days in the study locations. **ARY:** Study location of Arawraye, **BRK:** Barokoira; **BSG:** Boussaragui; **DAM:** DaraAmadou; **DMB:** Dembo; **DJM:** DjindeMario; **GIY:** GadeIya; **KRK:** Karakara; **MAK:** Maiki; **MYR:** Mayara; **SBG:** SarkinBindiga; **SSB:** SayeSabuwa; **TCK:** Tchake, **WRZ:** Warzou, **ZFT:** Zebane Fiti

4.1.3.2.Genetic gain of cowpea genotypes observed from the on-farm trials

Positive genetic gain was obtained for pod yield in six study locations out of fifteen where the average pod yield of the selected varieties was higher than that of the control varieties. The highest positive genetic gain (600.1) with the CS012, was observed in the village of Arawraye (Fig.33).

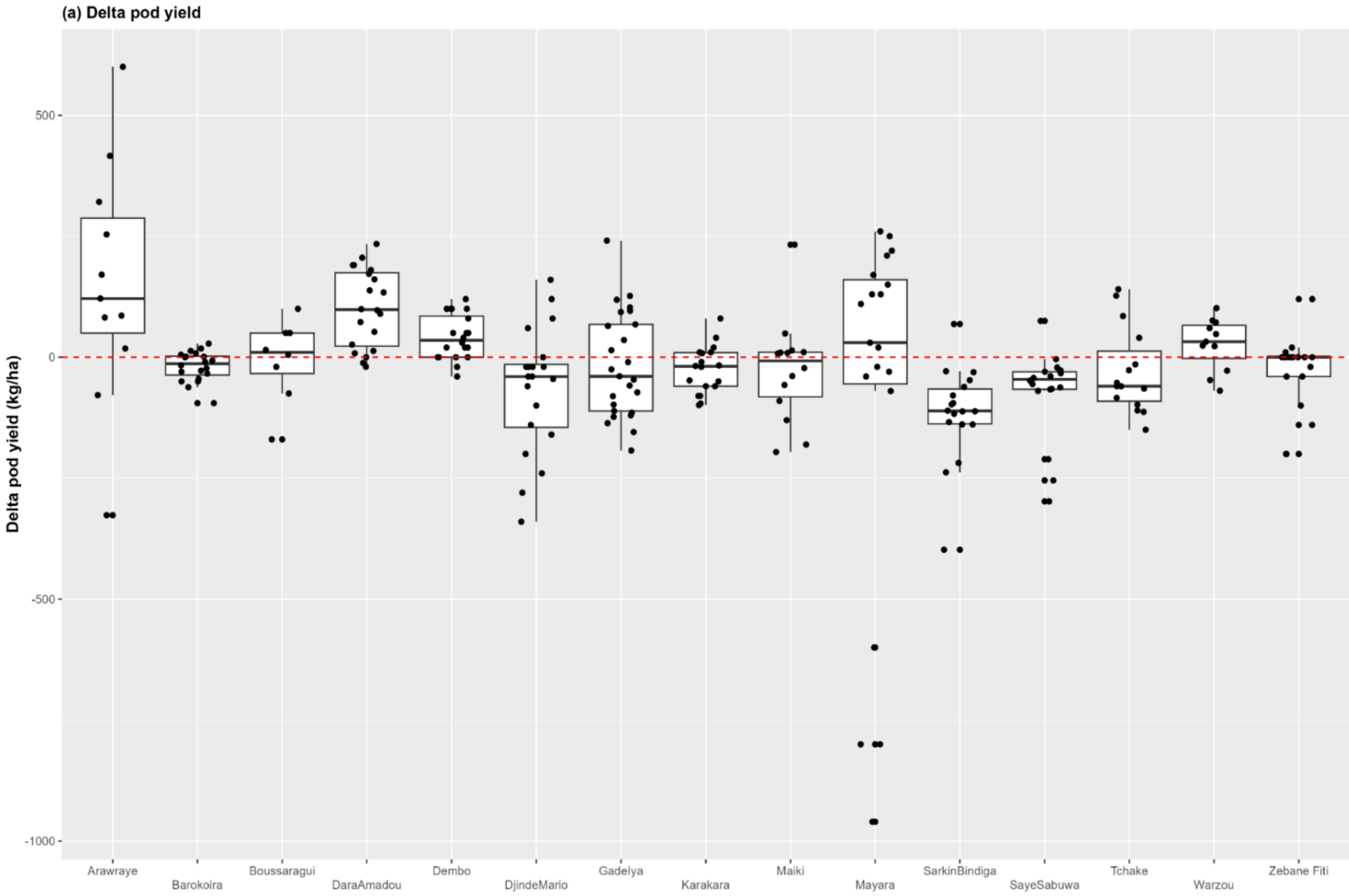

Figure 33: Difference (Δ) between the pod yield of the selected cowpea genotypes and the control cowpea varieties showing the genetic gain observed in some of the study locations

For the haulm yield, the genetic gain was positive in nine villages out of the fifteen with the highest positive genetic gain recorded in Djinde (4,360) (Fig.34).

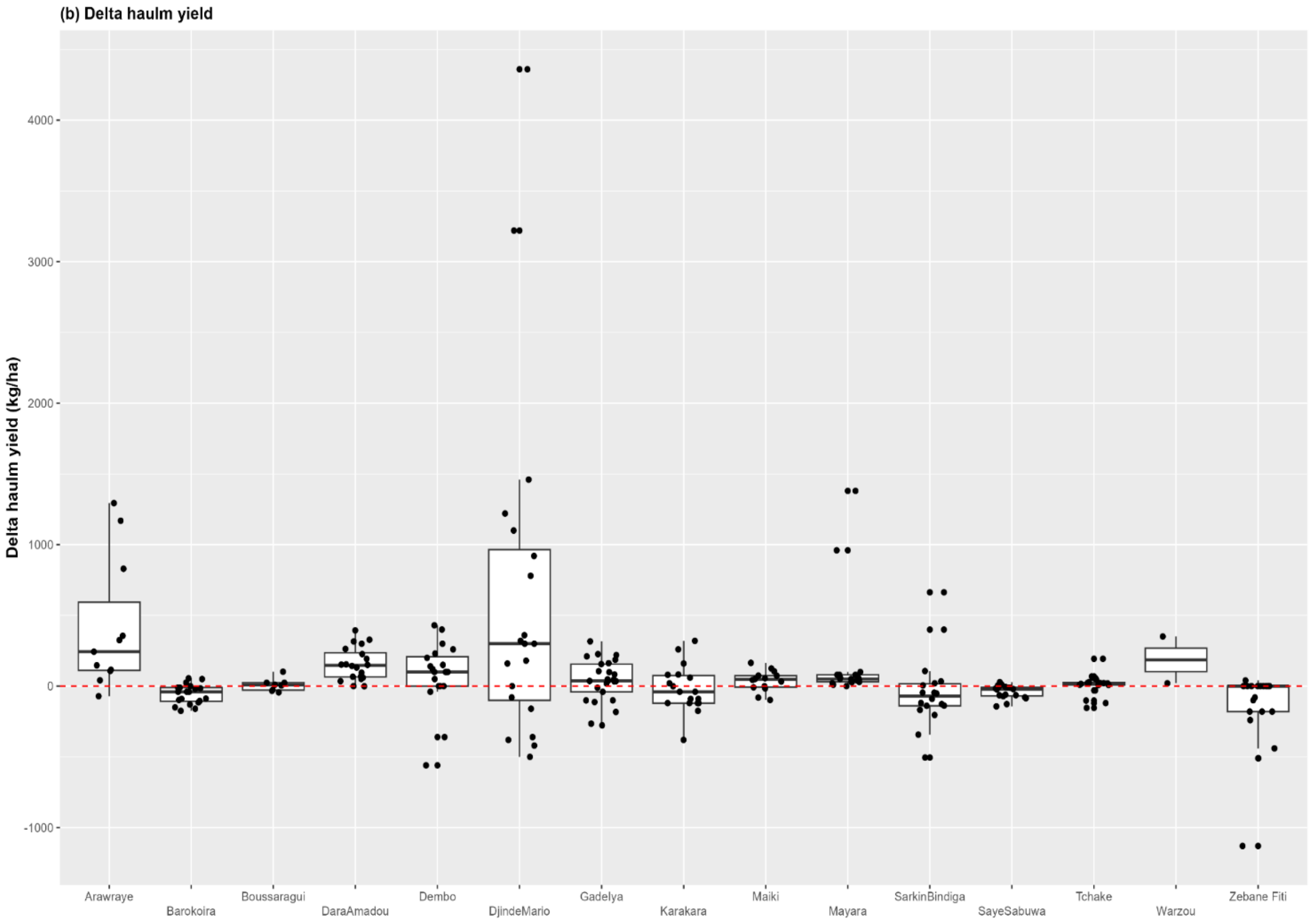

Figure 34: Difference (Δ) between the haulm yield of the selected cowpea genotypes and the control cowpea varieties showing the genetic gain observed in some of the study locations

4.1.3.3. Evaluating the cowpea genotype performance with the compared cowpea varieties

In all the fifteen study locations, significant differences were found for pod and haulm yields and the dual-purpose index (DPI) in these five respective study locations: Arawraye, DaraAmadou, Dembo, BaroKoira, SayeSabuwa (Table.13). Both the selected varieties (classical) and the selected varieties (multiline) showed significant differences in pod and haulm yields and the DPI respectively in Arawraye and Dembo and DaraAmadou compared to the control varieties and the opposite trend was observed with the last two study locations i.e., BaroKoira, SayeSabuwa.

Table 13: Summary of the Wilcoxon test output of all the study locations showing the level of significance for each of the three yield traits

Legend: The figures in brackets: "**1**": means that the selected variety is significantly higher than the control variety, "**-1**" means the opposite trend, and "**0**" shows that there is no significant difference between the selected varieties and the control varieties. "**NS**" in the brackets means non-significant.

Village	Variety name	Pod yield	Haulm yield	DPI	N	List of control varieties[2]
Arawraye	CS012	1 (0.05)[3]	1 (<0.05)	1 (<0.05)	20	Bawchin jirgui (1), Dan bauch (3), Dan gawgawa (1) Dan jaho (1), Gouchine zirgui (1), IT90 (mai jan hanci) (2), Koukan djirgui (1), Lakkade (3), Mai farine hantchi (1), Mai hitila (4), Mai yadiya (1), Zizal zirgui (1)
Barokoira	CS052	-1 (<0.05)	-1 (<0.05)	-1 (<0.05)	20	Doungouri koirey (6), IT90 (mai jan hanci) (2), Nina bi (2), Nina kirey (5), Tchekole (5)
Dembo	CS127	1 (<0.05)	1 (<0.05)	1 (<0.05)	20	Dan hadjia (3), Dan izala (1), Dan jaho (1), Dan jan kudi (1), Dan watsatsa (3), Dan zahi (1), IT90 (mai jan hanci) (10)
DjindeMari o	CS001	-1 (0.05)	1 (<0.05)	0 (NS)	20	Doungouri kassa (1), Doungouri koirey (6), Gnagaou (1), IT90 (mai jan hanci) (1), KVX (11)

[2] The list represents the control varieties compared with the selected varieties across the study sites. Figures in brackets are the number of farms in which the control variety was used during the test.
[3] This represents the summary of the level of significance of the Wilcoxon text. The figures of the p-value are presented in the annex 3.

Karakara	CS001 (8), CS126 (10)	-1 (<0.05)	0 (NS)	0 (NS)	18	Babban wake mai harawa (6), Babban wake mai lankwassa (5), Da kanta uban diya (1), Dan yagaou (4)
SayeSabuwa	CS134 (20)	-1 (0.001)	-1 (0.001)	-1 (<0.001)	18	Dan batsake (1), Dan hadjia (1), Dan jan kudi (1), Dandam (3), Lakkade (14)
Zebane Fiti	CS134 (20)	0 (NS)	-1 (<0.05)	-1 (<0.05)	20	Doungouri Bero (1), Doungouri koirey (9), Talhana (4), Wande mardje (3)
Boussaragui	CWS-RIL-31-38-35	0 (NS)	0 (NS)	0 (NS)	20	Dan Aloka (1), Dan Illa (2), Dan jan kudi (1), Dan kourourou (1), Dan zahi (1), IT90 (mai jan hanci) (2), Lakkade (2)
DaraAmadou	CWS-RIL-31-38-37 (10), CWS-RIL-31-38-46 (10)	1 (<0.05)	1 (<0.001)	1 (<0.001)		Dan hadjia (3), Dan izala (1), Dan jaho (1), Dan jan kudi (1), Dan watsatsa (3), Dan zahi (1), IT90 (mai jan hanci) (10)
GadeIya	CWS-RIL-5-30-12 (13), CWS-RIL-5-30-2 (1), CWS-RIL-5-30-8 (4), CWS-RIL-5-30-9a (1), CWS-RIL-5-30-9b (6)	0 (NS)	0 (NS)	0 (NS)	25	Dandam (1), Hannun marini (10), Lakkade (13), Mai bakin kono (1)
Maiki	CWS-RIL-31-38-3	0 (NS)	0 (NS)	0 (NS)	19	Dan watsatsa (1), Dandam (2), IT90 (mai jan hanci) (1), Lakkade (16)
Mayara	CWS-RIL-31-38-35	0 (NS)	1 (<0.05)	0 (NS)	20	Barta tatafi (1), Dan gawgawa (2), Dan izala (3), Dan jan kudi (1), Farin wake (5), IT90 (mai jan hanci) (5), Mai hitila (2)
SarkinBindiga	CWS-RIL-31-38-2 (2), CWS-RIL-31-38-20 (2), CWS-RIL-31-38-28 (1),	-1 (<0.001)	0 (NS)	-1 (<0.001)	20	Bahaushe (3), Dandam (6), Hannun marini (5), Lakkade (6)

	CWS-RIL-31-38-49 (3), CWS-RIL-31-38-50 (7), CWS-RIL-31-38-7 (5)					
Tchake	CWS-RIL-31-38-35 (2), CWS-RIL-31-38-49 (2), CWS-RIL-31-38-52 (5), CWS-RIL-31-38-56 (1), CWS-RIL-31-38-6 (3), CS133 (7)	0 (NS)	0 (NS)	0 (NS)	20	Dan bauchi (13), Dan watsatsa (2), Mai hitila (4)
Warzou	CWS-RIL-31-38-38 (1), CWS-RIL-31-38-39 (1), CWS-RIL-31-38-40 (1), CWS-RIL-31-38-41 (1), CWS-RIL-31-38-42 (1), CWS-RIL-31-38-43 (1), CWS-RIL-31-38-44 (1), CWS-RIL-31-38-45 (1), CWS-RIL-31-38-46 (1), CWS-RIL-31-38-47 (1), CWS-RIL-31-38-48 (1), CWS-RIL-31-38-49 (1), CWS-RIL-31-38-50 (1), CWS-RIL-31-38-51 (1), CWS-RIL-31-38-52 (1), CWS-RIL-31-38-53 (1), CWS-RIL-31-38-54 (1), CWS-RIL-31-38-55 (1), CWS-RIL-31-38-56 (1), CWS-RIL-31-38-57 (1)	0 (NS)	0 (NS)	0 (NS)	20	Dan bauchi (11), `Dan jan kudi (1), Dan tchabague (1), Godosso mai bakin hanci (1), Haoukan kowa (4), IT90 (mai jan hanci) (1), Mai tsanwayan diya (1)

Table 14: Summary of the Wilcoxon test output of all the case study of the selected cowpea genotypes/varieties where at least 20 farmers tested the selected varieties in at least one study location

Legend: The figures in brackets: "**1**": means that the selected variety is significantly higher than the control variety, "**-1**" means the opposite trend, and "**0**" shows that there is no significant difference between the selected varieties and the control varieties. "**NS**" in the brackets means non-significant.

Village	Variety name	Pod yield	Haulm yield	DPI	N of farmers	List of control varieties
(a) Selected varieties (multiline)						
Maiki	CWS-RIL-31-38-3	0 (NS)	0 (NS)	0 (NS)	19	Dan watsatsa (1), Dandam (2), IT90 (mai jan hanci) (1), Lakkade (16)
Boussaragui	CWS-RIL-31-38-35	0 (NS)	0 (NS)	0 (NS)	20	Dan Aloka (1), Dan Illa (2), Dan jan kudi (1), Dan kourourou (1), Dan zahi (1), IT90 (mai jan hanci) (2) , Lakkade (10)
Mayara	CWS-RIL-31-38-35	0 (NS)	1 (<0.05)	0 (NS)	20	Barta tatafi (1), Dan gawgawa (2), Dan izala (3), Dan jan kudi (1), Farin wake (5), IT90 (mai jan hanci) (5), Mai hitila (2)
(b) Selected varieties (classical)						
DjindeMario	CS001	-1 (0.05)	1 (<0.05)	0 (NS)	20	Doungouri kassa (1), Doungouri koirey (6), Gnagaou (1), IT90 (mai jan hanci) (1), KVX (11)
Arawraye	CS012	1 (0.05)	1 (<0.05)	1 (<0.05)	11	Bawchin jirgui (1), Dan bauchi (3), Dan gawgawa (1), Dan jaho (1), Gouchine zirgui (1), IT90 (mai jan hanci) (2), Koukan djirgui (1), Lakkade (3), Mai farine hantchi (1), Mai hitila (4), Mai yadiya (1), Zizal zirgui (1)

Barokoira	CS052	-1 (<0.05)	-1 (<0.05)	-1 (<0.05)	20	Doungouri koirey (6), IT90 (mai jan hanci) (2), `Nina bi (2), Nina kirey (5), Tchekole (5)
Dembo	CS127	1 (<0.05)	1 (<0.05)	1 (<0.05)	20	Boulibala (2), Doungouri kirey (2), Doungouri koirey (10), Kirmitia (6)
SayeSabuwa	CS134	-1 (0.01)	-1 (<0.01)	-1 (<0.01)	18	Dan batsake (1), Dan hadjia (1), Dan jan kudi (1), Dandam (3), Lakkade (14)
Zebane Fiti	CS134	-1 (0.05)	-1 (0.05)	-1 (0.05)	20	Doungouri Bero (1), Doungouri koirey (9), Talhana (4), Wande mardje (3)

Table 15: Summary of the Wilcoxon test output of the case study of the most used control varieties by farmers where at least 20 farmers used it as the compared variety to the selected ones

Legend: The figures in brackets: "**1**": means that the selected variety is significantly higher than the control variety, "**-1**" means the opposite trend, and "**0**" shows that there is no significant difference between the selected varieties and the control varieties. "**NS**" in the brackets means non-significant.

Village	Variety name	Pod yield	Haulm yield	DPI	N of farmers	List of compared CS varieties
(a) Doungouri koirey						
Barokoira	Doungouri koirey	-1 (<0.05)	-1 (<0.05)	-1 (<0.05)	6	CS052 (6)
Dembo	Doungouri koirey	1 (<0.05)	0 (NS)	0 (NS)	10	CS127 (10)
DjindeMario	Doungouri koirey	0 (NS)	0 (NS)	0 (NS)	6	CS001(6)
Zebane Fiti	Doungouri koirey	-1 (0.001)	-1 (<0.05)	-1 (<0.05)	8	CS134 (9)
(b) Lakkade						
Boussaragui	Lakkade	0 (NS)	0 (NS)	0 (NS)	5	CWS-RIL-31-38-35 (10)
Maiki	Lakkade	0 (NS)	0 (NS)	0 (NS)	10	CWS-RIL-31-38-3 (16)
SarkinBindiga	Lakkade	-1 (<0.05)	-1 (<0.05)	-1 (<0.05)	6	CWS-RIL-31-38-20 (1), CWS-RIL-31-38-28 (1), CWS-RIL-31-38-49 (1), CWS-RIL-31-38-50 (2), CWS-RIL-31-38-7 (1)
GadeIya	Lakkade	0 (NS)	0 (NS)	0 (NS)	13	CWS-RIL-5-30-12 (6), CWS-RIL-5-30-8 (3), CWS-RIL-5-30-9b (4)

SayeSabuwa	Lakkade	-1 (0.05)	-1 (<0.05)	-1 (<0.05)	12	CS134 (14)
(c) IT90 (mai jan hanci)						
DaraAmadou	IT90 (mai jan hanci)	1 (<0.05)	1 (<0.05)	1 (<0.05)	10	CWS-RIL-31-38-37 (4), CWS-RIL-31-38-46 (6)
Mayara	IT90 (mai jan hanci)	0 (NS)	0 (NS)	0 (NS)	5	CWS-RIL-31-38-35 (5)

The case study of the statistical test of the selected genotypes (Table.14) revealed that the selected varieties (multiline) yielded significantly more haulm (P≤0.05) in only one study location of Mayara while significant differences (P≤0.05) were observed for all the three yield parameters in Arawraye and Dembo.

However, I identified three control varieties that significantly performed better (P≤0.05) than the selected varieties for the three yield components (Table.14). These varieties were: Doungouri koirey (DK), Lakkade and IT90 (mai jan hanci). The majority of the farmers in the West (in four villages out of five) used DK as the control plots while Lakkade and IT90 (mai jan hanci) (in 7 villages out of ten). The name of these varieties is in the local language.

The graphical representation showed that the largest cowpea pod yield of 380.5 kg. ha-1 was recorded with the variety CS012 which is among the selected varieties (classical) followed by the genotype CWS-RIL-31-38-46 (multiline) which recorded 284.5 kg. ha-1 in DaraAmadou (Fig.35).

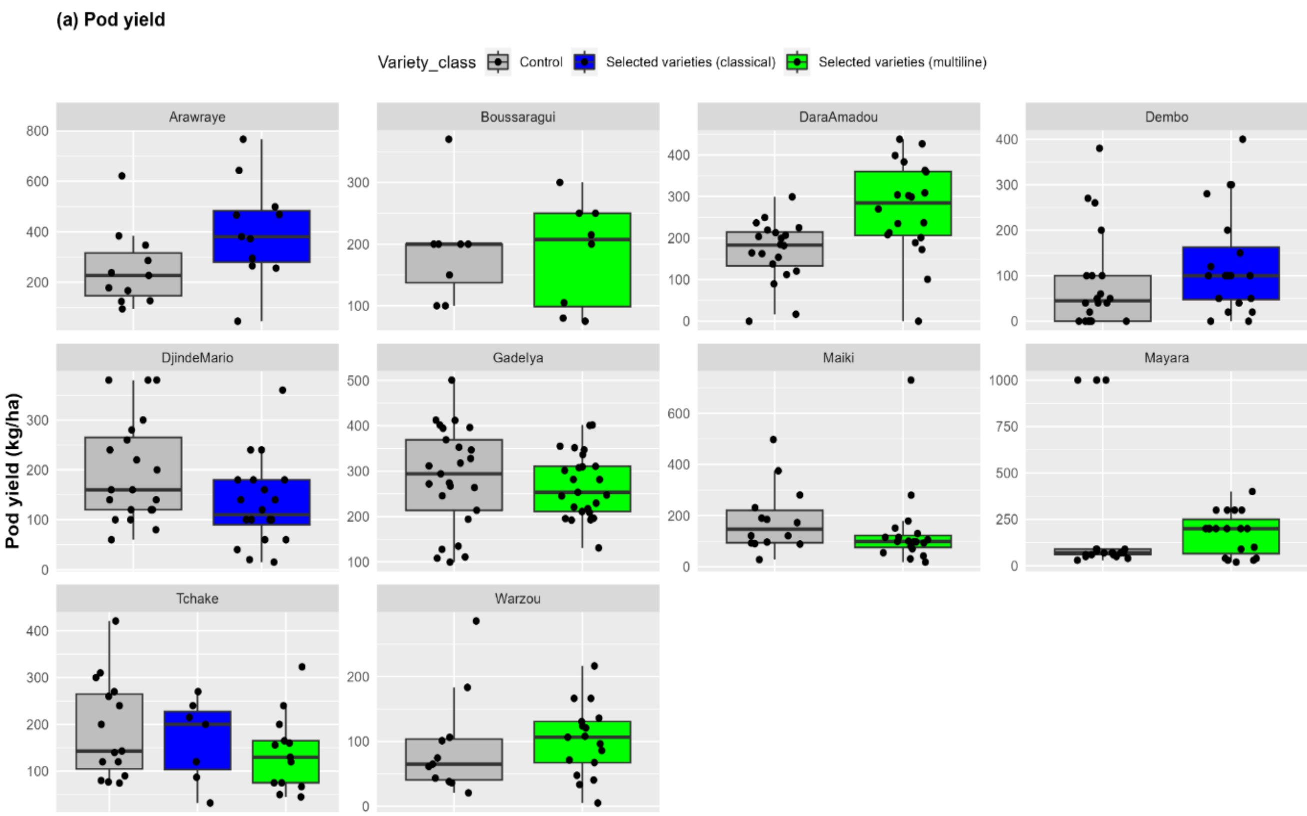

Figure 35 : Performance in pod yield of the selected cowpea genotypes (classical and or multiline) observed in the ten villages out of the fifteen study locations

Similarly, the CS012 yielded the highest haulm yield with 1,078 kg. ha-1 followed by the CS001 with 780 kg. ha-1 (Fig.36).

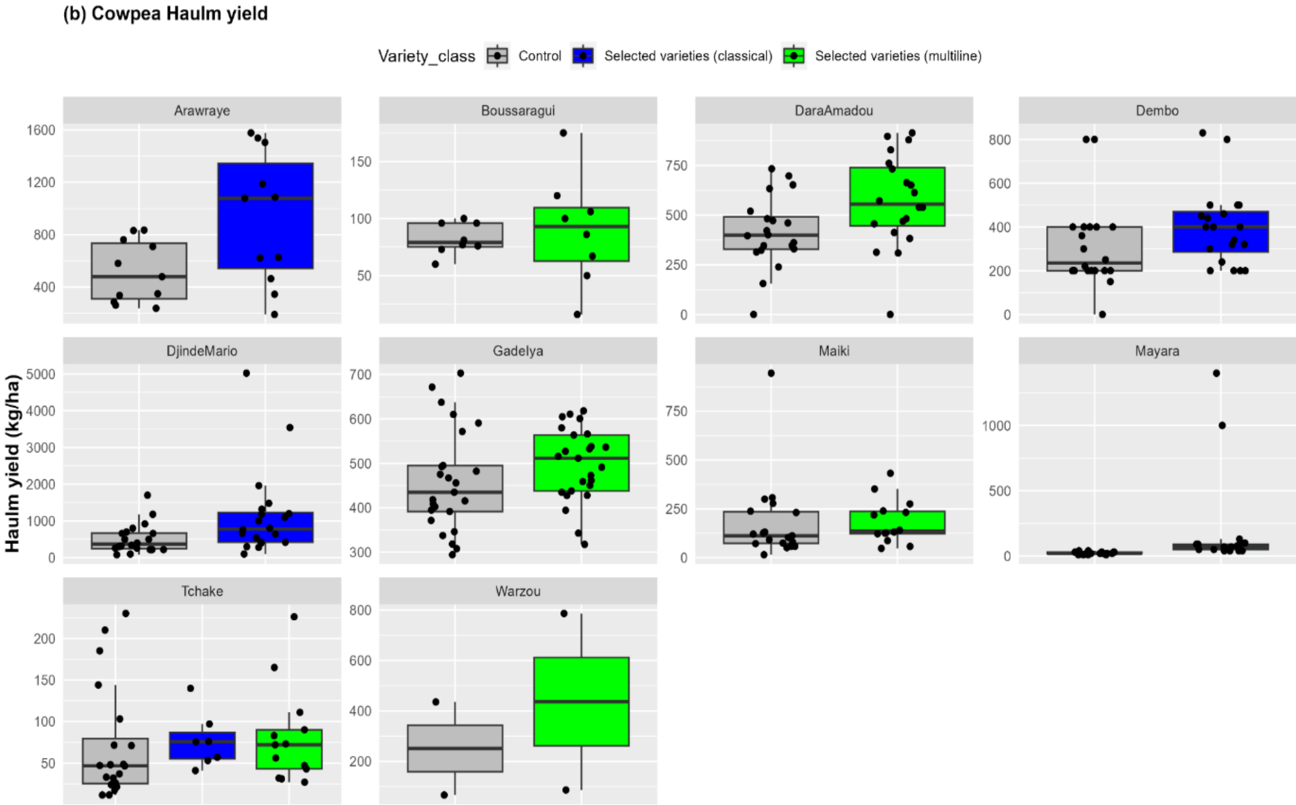

Figure 36: Performance in haulm yield of the selected cowpea genotypes (classical and or multiline) observed in the study locations

Amongst the selected varieties (classical), the largest dual-purpose index was obtained with the CS001tested in Djinde Mario with 1285 whereas, the CWS-RIL-31-38-46 yielded better DPI among the selected varieties (multiline).

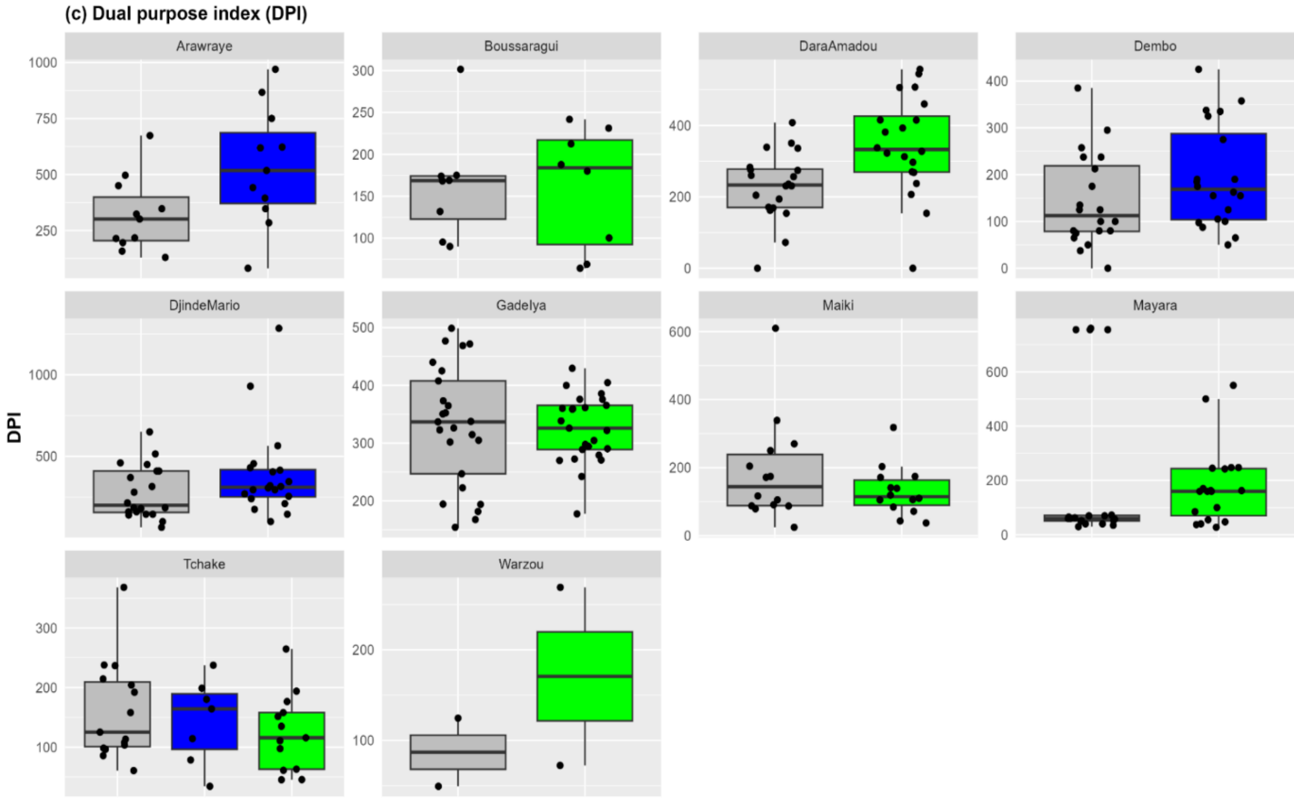

Figure 37: Performance in the dual-purpose index (DPI) of the selected cowpea genotypes (classical and or multiline) observed across the study locations

4.2. Discussion

4.2.1. Part I: Characterizing family farms and their constraints and AEI options for innovation: A case study from the Sahelian zone, Niger

4.2.1.1. Do family farms in the Sahelian context cope with the negative impacts of climate change based on their resource endowment?

From the results of the study, family farms members are young with an average age of 47 years old and 87.15% of the members are married while 74.31% are male and 25.68% are female. These results are consistent with the last census carried out by the government of Niger (INS, 2013) which indicated that the majority of the Nigerien population are young and the proportions of family farms led by male and female were 93.4% and 6.6% respectively. In addition, the main activity in family farms is agriculture (98.16%) as farmers highlighted this as the main source of income. The study revealed that the second major sources of income of the family farms members is animal husbandry and trading and farmers averagely possess 2 cattle, 4 goats and 3 sheep. Thus, these results are similar to that of (Mutaqin, 2019) who indicated that smallholder farmers rear animals by diversifying their economic activities as a coping strategy to sustain their livelihoods and minimize the adverse impacts of climate change. Therefore, in Niger, the main reason why animal husbandry is practiced in the family farms is because of its capacity to generate income by means of selling the livestock and or the meat, milk, and skins they produce. Added to that, it is the main source of organic fertilizer to increase crop productivity and it represents a great means of transportation. Nevertheless, some households are self-consumers of their livestock products. Thus, animal husbandry can significantly improve the nutritional quality of their diet, while healthy nutrition also has an effect on poverty reduction through improved productivity and competitiveness of individuals in the labour market (Bocoum et al., 2013).

Further, the study shows that family farms are characterized by the presence of the main field and the field led by the female, mostly the spouse of the head of the household. The presence of the field managed specifically by the female could be due to the level of awareness in the study area to empower women to strengthen the resilience of the family farms. Women provide a significant labour input at only 27% in crop production in Niger (World Bank, 2023). Yet, this figure can be questionable because the respondents lack key information, they may over or under-estimate the accurate level of contribution of female household in agricultural tasks. The findings are similar to that of the FAO, (2014) which highlighted an acceptable share that women contribute in agricultural labour in family farm across sub-Saharan African countries as they operated family farms on average only one half to two-thirds the size of those operated by men.

Further, it was observed that in most of the family farms, the field led by the women are located near the village and thus they are more diverse concerning the cultivation of more crop species than the main field. Therefore, the larger crop diversity found in the family farms could be as result of the presence of these fields led by the women (Fig.13). Farmers mainly use the main field to solely cultivate the staple crops such as millet, sorghum and cowpea for the subsistence of the family farming while a diversity of cash crops are grown in the WF to increase their income. It is obvious that the WF play a crucial role in not only empowering women but also to improve food security and to cope with the climate change impacts. These WF can therefore be considered as home gardens of the study locations. Thus, the WF like the home gardens appear to be the adaptation strategies to climate change while simultaneously contribute to food security and nutrition among women and young children in Africa (Hansen *et al.*, 2022).

Regarding the surface of the fields in the family farm, our study pointed out that the majority of the main fields and the WF are averagely less than 5 ha and 2 ha respectively. It is therefore evident that family farms in our study are small in size. Similarly, the FAO, (2014) found that 95% of farms are smaller than 5 ha and constitutes the majority of the farmland in sub-Saharan African while 20 % of farms are less than 1 ha and represent 20% of the same region. Furthermore, it was estimated that the average of farm size decreases in most of the developing countries due to many challenges (Lowder *et al.*, 2016).

In short, our study showed that in spite the strength of the family farms based on their structure and resources to limit the adverse impacts of climate change, the context of family farming is rapidly changing because of many factors such as the biophysical factors, socio-economic challenges and climate hazards. For instance, in Taranaki, it was observed a decline of the family farms caused by the above-mentioned drivers (Duncan, 2016).

4.2.2. Part II: Co-building an integrative and transdisciplinary trial design for the implementation of agroecological options in the context of local family farms: A pilot methodological experiment in Niger

4.2.2.1. The "options by contexts" (OxC) approach in the integrative and transdisciplinary trial design

In the co-design process of the integrative trial design (Fig.27), four main steps were developed to implement the trial. These steps indicated a strong application of the participatory research approach. For instance, the first step aimed at identifying the AEI options suitable to farmers' contexts. Unlike the oriented-input agriculture, the AEI options were selected in a participatory way (brainwriting, meeting with farmers and extension officers and researchers). A thorough analysis of the options and the context-specific for farmers' needs were also considered to establish the combined AEI options to be tested. We then applied rigorous and democratised research processes to achieve the goals of the study. Thus, applying the FRN approach in the integrative trial design process (Rebecca et al., 2019; Richardson et al., 2021) could be more useful for farmers to adopt the combined AEI options in a scalable manner.

A wide variability of the effects of the individual AEI options was found across the study locations.

For instance, in Garke and Kaboye Koira (Western part of Niger), the CS039 cowpea variety yielded better than the CS126 in both of the CS options. The opposite trend was found in Gwassale while there was no significant difference between the two varieties in Saye Sabuwa. In response to the SFM options, a huge variability was noticed where the decomposed manure increased cowpea yields compared to the use of DAP fertilizer as a micro-dose in Gwassale and Saye Sabuwa. Whereas in Garke and Kaboye Koira, higher cowpea yields were obtained with the use of DAP fertilizer micro-dose. This variability highlighted that the performance of AEI options depends on the local contexts. Combined AEI options that yielded good performance in a contrasted area may not perform well in the other areas even if soil types, cropping systems and climate conditions are relatively similar. While across the study locations, the average rainfall is a bit higher in the Centre-South than in the Western part, soil physical and chemical properties were less identical. These results were similar to that of (Falconnier et al., 2016; Masvaya et al., 2017; Rusinamhodzi et al., 2012, 2016; Sanou et al., 2016) across sub-Saharan Africa.

Most importantly, a larger variability might be found if both large on-farm trials and several farmers were taken into consideration in this integrative design. This considerably limits producing large-scale recommendations that meet the needs of farmers. There is a need for new ways of supporting innovation which address the real-world heterogeneity of farmer circumstances and hence the emergence of the OXC approach aims at addressing this challenge (Sinclair & Coe, 2019). These emphasized that the approach was regarded as an avenue that addresses the heterogeneity by recognizing that many of the factors that affect the suitability of agronomic innovations, such as soils, climate, farming practices, household characteristics, markets, social capital and policy implementation, vary at a fine scale. Like our study aimed at identifying the promising combined AEI options adapted to local contexts, some studies (Berre et al., 2019, 2022; Descheemaeker et al., 2019; Dumont et al., 2019) attempted at tailoring options that fit smallholder farmer’s needs. This study tried applying the approach of OXC since the integrative trial has been implemented across four study areas with different rainfall gradients and farming practices. This study sought to find out the variability of the combined AEI option’s effects in two different agroecological zones of Niger by considering farmers’ perspectives. Hence, it went beyond the genotype-by-environment (GXE) interactions to assess the combined AEI options. For instance, farmers rated highly the combined AEI options (A1-A4) compared to the B1-B4 options (Fig.21) not because low yields were recorded from these options but because they included because of the socio-economic dimensions before selecting the combined AEI options. This was emphasized in the synthesis of the OXC approach (Sinclair & Coe, 2019) being an operational approach to supporting agronomic innovation at scale. Illustrative examples of OXC interactions that went beyond crop performance (in terms of crop yield) to accept innovation are many. (Hannatou et al., 2021) found strong interaction effects between fertilizer responses (application of sanitized human urine and or in combination with organic manure) and local soil types in women’s fields. The same type of interaction was found by (Sanou et al., 2016; Vanek & Drinkwater, 2019). (Falconnier et al., 2016) found strong interactions between fertilizer responses, crop types (cereal and legume) and soil types as defined by farmers. Thus, the concepts of options, contexts and performance are useful in the quest of identifying suitable solutions for farming systems but their application requires care because factors may change their status when a problem is looked at from different perspectives (Sinclair & Coe, 2019). Whether the integrative trial will fit the matching of more complex options with the enormous heterogeneity of contexts faced by smallholder farmers, its application in a scalable manner will be useful in advancing the agroecological transition in the Sahel.

4.2.2.2. Combined AEI options in the context of smallholder farmers of Niger

With IVMs mainly above zero (Fig.29) across the study locations, smallholder farmers appreciated well the combined AEI options. Nevertheless, farmers were motivated to adopt some of the combined AEI options, including organic manure, intercropping, and dual-purpose cowpea varieties compared to DAP micro-dose and the sole cropping of cowpea because of the significant crop yield recorded from these AEI options. This may also be because the decomposed organic manure is more cost-effective and easily accessible for them. Similarly, intercropping of millet with the dual-purpose cowpea varieties increases crop productivity and leads to household food security and reduces crop failure with the recurrent climate variability and change in the Sahel. This finding is similar to that of studies on Sahelian sandy soil in Burkina Faso and Niger (Ibrahim et al., 2015; Sanou et al., 2016). Farmers seem to be more interested in applying decomposed manure compared to mineral fertilizer but they appreciated combining these SFM options. However, adopting the combined AEI options for farmers is greatly dependent on some limiting factors which include climate, soil fertility status, climate, land and livestock holding, labour availability and farmers' awareness of the importance of combining AEI options to improve their livelihoods (Falconnier et al., 2016; Giller et al., 2011; Masvaya et al., 2017; Zingore et al., 2007). Although farmers appreciated the combined AEI options, in the Sahelian family farms, cowpea production remains a challenge because of farmers' low income limiting them to purchase good improved seeds. Besides that, cowpea grows well in the family farms of Niger and even on sandy soils, but most of the varieties are very sensitive to pests, especially aphids which can significantly decrease cowpea yield ranging from 20 to 42% (Zakari et al., 2019). Across the four study locations, pests were relatively absent and hence any biopesticide was not sprayed. Mostly, farmers control the pests with the neem seeds' aqueous extract biopesticide and or biopesticide cocktails which are readily accessible to them. Two improved cowpea varieties among the AEI options were used because they are well adapted to the local contexts. Although, smallholder farmers often cannot afford new varieties because of their low revenue, thanks to the participatory research project i.e., CowpeaSquare which enhances cowpea varietal diversity to fit farmers' needs in a contextualized manner at selected locations in Niger including our study locations (CCRP, 2022).

Soils in the study area were sandy and nutrient- and the use of SFM options (decomposed manure at the planting hole and DAP as micro-dosing) may reduce the quantity of fertilizer N and P required by pearl millet and cowpea in the short term. There was no significant difference between the use of decomposed organic manure and the DAP fertilizer as a micro-dose (Table 9). Nevertheless, reports from previous studies (Ibrahim et al., 2016; Ibrahim et al., 2015; Ibrahim et al., 2015; Tabo et al., 2011) showed that the application of mineral fertilizer micro-dosing alone or combined with manure increased crop yield by up to 100%, and farmers' incomes went up by 130% when micro-dosing was combined with the warrant system. However, in the longer term, micro-dosing application of either organic manure or mineral fertilizer leads to nutrient mining which affects the production (Sani et al., 2020; Ibrahim et al., 2016). This micro-dosing fertilizer application technique is appealing to poor farmers who cannot afford large fertilizer quantities (Tabo et al., 2011). There is a need to sustainably intensify the farming system in the Sahel as with cropping systems and soil fertility management options, both cowpea and millet nutrient requirements should be addressed. Organic matter supply is at the forefront of improving crop productivity given its low level (≤1%) in the study areas ((Mahaman Sanoussi, 2016). As such, organic manure is a key nutrient resource on family farms as it provides both macro- and micronutrients (Bationo et al., 1998; Mariana, 2008; Zingore et al., 2007) followed by the use of compost, biochar etc. despite their labour costs.

4.2.2.3. Do the combined AEI options comply with the agroecological principles?

The United Nations Food and Agriculture Organization (FAO) described agroecology (AE) in terms of 10 Elements (FAO, 2018). They used this framework to design the Tool for Agroecology Performance Evaluation (TAPE) for the assessment of the agroecological state of farms and landscapes as part of their mission to produce globally comparable data(Mottet et al., 2020) while the same tool was critically c analysed for its adaptability to local contexts of smallholder farmers in Eastern Africa (Namirembe et al., 2022). In this study, the selected AEI options are in line with these AE principles for application on the ground. For example, among the two SFM options, the use of decomposed organic manure in smallholder farms supports greatly the following principles: Diversity, efficiency, recycling and synergy. Whether decomposed or not, organic manure increases vertical diversity while it is being recycled to feed the soil for increased crop production to feed the people. Crop-livestock integration is an effective means by which nutrients can be rapidly recycled within and between farms, though care is needed to reduce the risk of inefficiency in the farming system (Alomia-Hinojosa, 2019; Franke et al., 2010; Mariana Cristina, 2008). On the other hand, applying mineral fertilizer does not comply with agroecological principles but when it is used efficiently like through micro-dosing is regarded as agroecological. This is a form of recycling for it enables farmers to use fewer external inputs which are highly described among the core agroecological principles (efficiency, recycling and reduction of external inputs) (FAO, 2018; HLPE et al., 2019). Intercropping millet-cowpea as the CS option enhances farmers' resilience by improving their income through crop diversification while synergy is applied to reduce pests and diseases and to increase soil fertility. Falconnier et al., (2016); Masvaya et al., (2017) and Rusinamhodzi et al., (2012) found that cereal-legume intercropping has the potential to enhance land-use efficiency through over-yielding compared with cereal sole cropping in spite of the time of intercropping, the quality of the season and the soil types in farming systems where the use of external inputs like fertiliser is limited. In the same context, the use of new crop varieties which are adapted to the local contexts enables smallholder farmers to cope with climate variability and change while other benefits such as an increase in genetic resources diversity and income diversification are secured. In the case of our study, findings showed that the two cowpea varieties were dual-purpose and can contribute to adapting to climate change. Thus, the use of these two varieties in the integrative trial design showed a greater application of the following AE principles diversity, synergy, resilience and co-creation and knowledge sharing compared to the remaining.

4.2.3. Part III: Performance of cowpea genotypes selected through participatory varietal selection and participatory breeding under different local contexts of the smallholder farmers in Niger

4.2.3.1. Cowpea productivity in the context of family farming systems

The study showed that the selected varieties either classical or multiline had a higher haulm yield than the local control varieties whereas some selected varieties recorded higher pod yield than the control varieties used by farmers. Despite the absence of insecticide spray during the trial, CS012, CS127, CWS-RIL-31-38-46 yielded better (above 200 kg. ha^{-1}) for both the pod and the haulm yields respectively in Arawraye, Dembo and DaraAmadou while CS001, CWS-RIL-31-38-35, and CWS-RIL-31-38-35 recorded advanced haulm yield (above 500 kg. ha-1) compared to all the control varieties respectively in Djinde Mario, Boussaragui and Mayara. This was presumably due to their vigorous flowering and ability to form pods and the "stay green” properties, which compensated for insect damage. However, when the insecticide and or the biopesticide or the botanical insecticide were applied, these pod and haulm yields would significantly increase but the instructions were given to farmers not to spray the insecticide for both the selected varieties and the control varieties plots. This was intentional in order to assess the level of tolerance and resistance to insects of the selected varieties as improved varieties are often sensible to insects.

Nevertheless, Yusuf et al., (2008) emphasized that the use of integrated pest management practices such as the use of resistant cowpea varieties, mixed cropping systems, botanical and reduced risk insecticides, and biological control assisted by pest monitoring seems to be considered as the key elements to a sustainable and increased cowpea production in West Africa.

Further, it was evident that intercropping generally depressed cowpea yield. This might be the reason why the yield of the selected varieties was not stable and good in some study locations. Testing the selected cowpea varieties in the intercropping system is most important because the farming systems across the study locations are millet-cowpea based systems. These findings are similar to that of Sanou et al., (2016) who found that intercropping cowpea and pearl millet increased significantly crop production with a land equivalent ratio = 1.83 ± 0.18 and 1.78 ± 0.20. Moreover, the main gains of cereal-legume intercropping are achieved when competition is significantly reduced and complementarity and facilitation increased (Masvaya et al., 2017; Rusinamhodzi et al., 2012, 2016).

4.2.3.2. How do dual-purpose cowpea varieties address a changing climate?

Climate change is undoubtedly one of the most serious challenges that the earth planet is facing in the 21st century as result of continuous temperature rise, causing numerous extreme weather events such as heat waves, droughts and floods (Mabhaudhi et al., 2019; Potner et al., 2022). Overall, these have caused significant crop yield decrease through several mechanisms, including changes in crop growth stages, heat stress, soil fertility and recurrent and prolonged droughts. The 2022 report of the working group II of the IPCC showed that food and forestry systems are already being stressed by climate variability and change, with negative consequences for the livelihoods, food security and nutrition of hundreds of millions of people, especially in low and mid-latitudes. Thus, the global food system is failing to address food insecurity and malnutrition in an environmentally sustainable way (Potner et al., 2022). Food security remains a major challenge in sub–Saharan Africa, mostly in the Sahel region.

Climate-resilient crops such as grain legumes can address this issue. Among the grain legumes, cowpea is a suitable smart food with a high contribution to food, feed and nutritional security and is good for being an option in extreme environments. The dual-purpose characteristics cowpea varieties are considered as an option to climate change adaption (Yaya et al., 2010). Cowpea is a climate-resilient legume as it has the ability to accommodate diverse cropping systems and contributes significantly to increase farmers revenue. It is evident that our multiline varieties can enable farmers to cope with the adverse impacts of climate change. The findings showed that these varieties are dual-purpose because of the higher dual-purpose index compared to the control varieties (Fig.37). In addition, despite the non-application of mineral fertilizer to the soil, both pod and haulm yields of the selected varieties significantly increased in ten villages compared to the control varieties. This may be due to the "stay green" property of these varieties especially the selected varieties (multiline) which proved to be more resilient than the selected varieties (classical). This characteristic of the selected varieties (multiline) inherited this morphological trait from their parent (a local land races variety) through the decentralized participatory breeding carried out from 2016 to 2019 (Fig.11). In this situation, cowpea could play a crucial role by providing diverse ecosystem services while adhering to agroecological principles (Vanlauwe et al., 2015). Further, cowpea is considered as an orphan crop which is the most nutritionally dense and climate-resilient, as it can accommodate to various cropping systems and is locally available for economic growth and social development (Mabhaudhi et al., 2019). Aside the capacity to fix free atmospheric nitrogen (N), deliver high-quality organic matter into the soil, and promote efficient soil nutrients cycling and water retention (Meena & Kumar, 2022), cowpea has the ability to create "live mulch" that decrease surface soil temperature and evaporation, thereby improving water conservation (Lima Filho, 2000). The selected cowpea varieties recorded higher haulm yield than the control varieties and the selected variety (CS001) in Djinde Mario yielded the largest haulm yield of 1.07 t. ha^{-1}. The one CGIAR programme on grain legume (Dar et al., 2012) highlighted that grain legume crops such as cowpea enables diversifying farming systems by making them more efficient, resilient and nutrient-efficient. Its rapid growth in the case of the new cultivars, not only improves protective soil cover, but also breaks the cycles of pests, diseases and weeds in cereal cropping systems. Further, diversifying farming activities with cowpea reduces the risk of catastrophic crop losses at farm level and hence increasing the resilience of farms to climate change. Our findings showed that the selected cowpea varieties are adapted to each local context where they were tested. Overall, cowpea can be used as a climate-resilient legume crop and can be cultivated even in the marginal land if minimum biophysical conditions are fulfilled.

4.3. General discussion

Exploring the combined AEI options for family farming systems requires the use of transdisciplinary research coupled with the participatory research approach. This indicates that it is evident to strengthen the synergy among researchers and farmers including policies. Most specifically, it is crucial to not only understand the complexity and the diversity of the family farmers but also knowledge on agroecological principles and management practices ((Alvarez et al., 2014; Berre et al., 2022; Kuivanen, Alvarez, et al., 2016; Kuivanen, Michalscheck, et al., 2016; Potential et al., 2020; Wezel et al., 2014). A set of approaches was used in this thesis to characterize the family farms, identify the key drivers impeding crop productivity, explore the AEI options practiced by farmers and evaluate both the proposed combined AEI options and the varietal options (the dual-purpose cowpea varieties). In this thesis, in the chapter 1 and 2, it was indicated that smallholder farming systems face many challenges such as inherent poor soil fertility, climate variability and change and low crop yields of the staple crops (millet and cowpea)(Bationo et al., 1998; Salack et al., 2018; A. Sanoussi et al., 2015; Schlecht et al., 2006). The findings in the chapter 4, part I confirmed the perceptions of farmers who highlighted the following as the key drivers in the family farms: decrease of soil fertility, increase of dry spells frequency and drought events, the decrease in crop yield, farmers low income and the limited access to market. This is the reason why the Sahel region and especially Niger is subjected to recurrent food insecurity and nutrition (FEWS-NET, 2019). Despite the presence of numerous AEI options across the family farms (Chapter 4, part I), it was observed that farmers do not practice or combine as many as possible in the same fields to increase the productivity. Increased labour, external puts use (new varieties, mineral fertilizers and or pesticides), less farmer participation in the new technologies/options development may be the possible causes. Alternatively, an integrative trial was co-designed (chapter 4, part II) among researchers and farmers to strengthen the synergy, to solve discipline partitioning and to facilitate farmers to combine many AEI options in their fields at the same time. The results from the pilot experiments showed that farmers tend to opt for the combination of the organic manure with intercropping millet-cowpea in the Centre-South while the intercropping and or the cowpea sole cropping systems combined with the micro-dosing option were most preferred in the West. This revealed the effect of option by context which shows that an option that performed best in one specific context may not in another context. Thus, targeting options to the contexts in which they yield better, helps to reduce risk and increase the adoption by farmers (Descheemaeker et al., 2019; Sinclair & Coe, 2019). Furthermore, the decentralized trials of the dual-purpose (chapter 4, part III) responded to the options by context approach which requires larger participation of farmers and options which perform best in a specific local context. The results showed that the dual-purpose cowpea varieties whether classical or candidate multiline recorded higher yields than the control ones in ten villages out of the fifteen. However, the dual-purpose cowpea varieties that performed better in Arawraye for instance may not produce much in another study location and vice versa.

Based on these results, designing the integrative trial coupled with the dual-purpose cowpea varieties in a scalable manner with considerable farmer participation at all the stages of the co-design process will enable meeting productivity and the farmers' livelihoods increase.

CHAPTER FIVE: CONCLUSION AND PERSPECTIVES FOR FUTURE RESEARCH

In summary, the main findings of the research revealed that family farms are mainly dependent on rainfed agriculture and they often rely on traditional modes of farming. One of the most important characteristics of family farms is the presence of the main fields and the field led by female which indicated that women contributed in the food security and nutrition. We found that the size of the whole farm is relatively small and the smallholder farmers produce mostly for subsistence. Nevertheless, female produce mainly cash crop which they sell to the local markets to generate income. Further, the study showed that the average yield of the staple crop (millet) and cowpea is smaller in the main field than in the field led by female. This indicated that the WF is more fertile due to their nearness to the village and hence they receive much quantity of organic manure in spite their smaller size. Our study shows that some key drivers significantly impede crop productivity in the family farming contexts. These are soil fertility decline, increase of dry spell frequency and the low income of smallholder farmers and the limited access to local markets. Our study analysed the adaptation measures used by the smallholder farmers to cope with these constraints such as the use of organic manure, the micro-dosing technique to improve soil fertility, the mixed intercropping as well as the FMNR technique and the compost to increase the productivity. However, further study should be conducted by using typologies to tailor these AEI options by taking into consideration the crop diversity, farm size and crop yield of both the MF and the WF. Furthermore, new ways of managing these practices are crucial to better increase crop productivity and the resilience of the smallholder farmers at large.

In this regard, options and specific contexts always matter when co-designing a participatory research approach. The participatory assessment showed that there was a wide variability effect of the combined AEI options across the study locations. Based on these findings, the hypothesis 1 and 2 I drew in chapter II were confirmed, which indicated that: (i) the agronomic performance of the combined AEI options depends on the biophysical and socio-economic conditions of the smallholder farmers and (ii) the innovative combination of AEI options that perform better represent pathways to increase crop productivity of smallholder farmers of Niger. Further, the four identified steps in the co-design process of the integrative trial to implement the combined AEI options can help overcome the key obstacles regarding disciplinary partitioning between researchers and the lack of methodology for knowledge and experience integration between academic and non-academic actors. From the design process up to the implementation and management of this pilot integrative trial, it was observed that piloting is an important step in deploying methods or tools to test and or assess innovations.

On the other hand, agricultural production in the Sahelian zone of Niger region faces multiple challenges, of which one of the most critical is the climate variability worsened by the inherent poor soil fertility. The study sought also to assess how do the new cowpea genotypes (classical and multiline) adapt to the local contexts of Niger and to compare the performance of these selected genotypes to the control varieties tested in the same biophysical conditions in each study locations. The main findings showed that the selected cowpea genotypes yielded better than the control varieties in ten study locations out of the fifteen. The two types of the selected cowpea varieties yielded differently due to differences in terms of genetic expression. These results confirmed my hypothesis 3 that pointed out higher yields are recorded by the selected dual-purpose cowpea genotypes/varieties than the control varieties. Moreover, the selected genotypes (multiline) are more dual-purpose compared to the selected genotypes (classical). These differences revealed a great opportunity to continue deploying genotypes not only in response to the needs of farmers and or yield increase but also in considering the adaptation to the local contexts.

In conclusion, I hereby highlight some take-home messages of my thesis:

- Developing technologies/options and approaches to increase crop productivity and farmers’ livelihoods without considering the diversified local contexts, farmers’ needs, and full participation at the project's early stage are less beneficial.
- Integrative trial design fills the gap of the lack of methodology integrating the experiences and knowledge of researchers and farmers.
- The most promising combined AEI options are pathways to minimize the adverse impacts of climate change in the Sahelian Niger and to improve the smallholder farmers’ livelihoods.

For the development of the research, further studies should be carried out to strengthen the adoption by farmers of the most promising AEI options in an integrative manner. I proposed the following perspectives to advance the scientific knowledge and to improve the livelihoods of the smallholder farmers of the Sahelian Niger:

- As typology is widely used to tailor management practices to structure farm households, and to identify recommendation domains (Berre et al., 2022), farm typologies should be used to tailor the agroecological intensification options by considering the crop diversity, farm size and crop yields as key variables of both the Main fields and the field.
- The agronomic performance of the combined AEI options is one thing and their economic performance is another thing. Although the involved stakeholders selected the most suitable AEI options in the step1 of the co-design process of the integrative trial, the cost-benefit analysis of the combined AEI options should be carried out to ensure that the promising combined AEI options are less costly regardless of their higher agronomic performance.
- Trade-offs' analysis of the combined AEI options should be conducted to verify whether the use of any combined AEI option leads to positive or negative trade-off.
- In my study, I only conducted the integrative trial in four pilot sites based on ecological gradient, it is still insufficient to draw general conclusion that some specific combined AEI options are adapted to these pilot sites. Therefore, there is a need to upscale the integrative trial design at territory level to identify the most promising combined AEI options adapted to the local contexts.

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APPENDICES

Annexe 1: FAMD outputs of the survey baseline

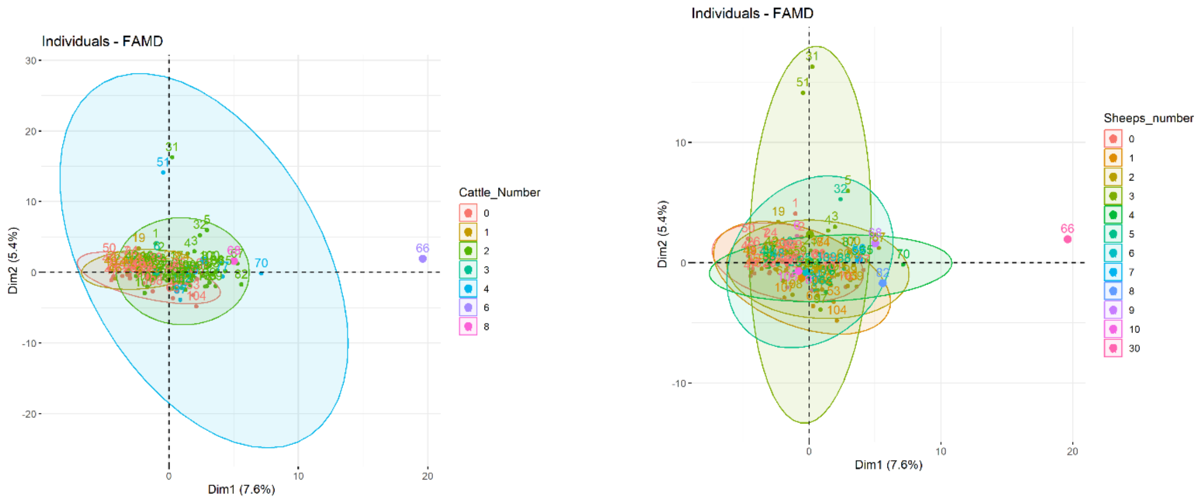


Figure 1: Distributed FAMD showing the livestock availability in the family farms

Figure 2: Distributed FAMD showing the presence/absence of the MF and the WF across the family farms

Annexe 2: Analysis of variance, linear mixed model and the remaining graphical representations of the integrative trial

Analysis of Variance Table1

Response: Grain_Yield_cowpea

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Village	3	117010	39003	7.2452	0.001616	**
Cowpea_variety	1	147	147	0.0274	0.870112	
Fertilization	1	69386	69386	12.8890	0.001723	**
Nb_of_shrubs_ha	1	20203	20203	3.7528	0.066287	.
Cowpea_variety:Fertilization	1	150	150	0.0279	0.868950	
Cowpea_variety:Nb_of_shrubs_ha	1	3	3	0.0005	0.982836	
Fertilization:Nb_of_shrubs_ha	1	2445	2445	0.4542	0.507701	
Cowpea_variety:Fertilization:Nb_of_shrubs_ha	1	14624	14624	2.7166	0.114191	
Residuals	21	113051	5383			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance Table2

Response: Haulm_Yield_cowpea

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Village	3	76040	25347	4.1386	0.018793	*
Cowpea_variety	1	767	767	0.1252	0.726949	
Fertilization	1	57141	57141	9.3300	0.006021	**
Nb_of_shrubs_ha	1	17202	17202	2.8088	0.108573	
Cowpea_variety:Fertilization	1	18892	18892	3.0848	0.093603	.
Cowpea_variety:Nb_of_shrubs_ha	1	569	569	0.0929	0.763473	
Fertilization:Nb_of_shrubs_ha	1	1882	1882	0.3072	0.585231	
Cowpea_variety:Fertilization:Nb_of_shrubs_ha	1	6056	6056	0.9888	0.331364	
Residuals	21	128613	6124			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance Table3

Response: Biomass_Yield_millet

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Village	3	771853	257284	5.2143	0.03331	*
Cowpea_variety	1	65068	65068	1.3187	0.28855	
Fertilization	1	60257	60257	1.2212	0.30565	
Village:Cowpea_variety	3	119289	39763	0.8059	0.52936	
Residuals	7	345393	49342			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Linear mixed model output for the combined AEI options

Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: Grain_Yield_cowpea ~ ((1 | Village) + Plot)

Data: Data_Agro

REML criterion at convergence: 295.9

Scaled residuals:

Min	1Q	Median	3Q	Max
-1.07606	-0.65207	0.02556	0.43546	2.37438

Random effects:

Groups	Name	Variance	Std.Dev.
Village	(Intercept)	4040	63.56
Residual		6683	81.75

Number of obs: 32, groups: Village, 4

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	78.501	51.776	12.038	1.516	0.155
PlotA2	43.600	57.806	21.000	0.754	0.459
PlotA3	3.637	57.806	21.000	0.063	0.950
PlotA4	56.948	57.806	21.000	0.985	0.336
PlotB1	-71.269	57.806	21.000	-1.233	0.231
PlotB2	-62.804	57.806	21.000	-1.086	0.290
PlotB3	-73.830	57.806	21.000	-1.277	0.215
PlotB4	-60.433	57.806	21.000	-1.045	0.308

Correlation of Fixed Effects:

(Intr) PlotA2 PlotA3 PlotA4 PlotB1 PlotB2 PlotB3

```
PlotA2 -0.558
PlotA3 -0.558  0.500
PlotA4 -0.558  0.500  0.500
PlotB1 -0.558  0.500  0.500  0.500
PlotB2 -0.558  0.500  0.500  0.500  0.500
PlotB3 -0.558  0.500  0.500  0.500  0.500  0.500
PlotB4 -0.558  0.500  0.500  0.500  0.500  0.500  0.500
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: Haulm_Yield_cowpea ~ ((1 | Village) + Plot)
   Data: Data_Agro
REML criterion at convergence: 290.9
Scaled residuals:
    Min      1Q  Median      3Q     Max
-1.9082 -0.5997  0.1219  0.4922  2.5181
Random effects:
 Groups   Name        Variance Std.Dev.
 Village  (Intercept) 2467     49.67
 Residual             5609     74.90
Number of obs: 32, groups:  Village, 4
Fixed effects:
            Estimate Std. Error      df t value Pr(>|t|)
(Intercept)   76.111     44.935  14.517   1.694  0.11164
PlotA2        95.278     52.960  21.000   1.799  0.08640 .
PlotA3        59.861     52.960  21.000   1.130  0.27109
PlotA4       151.944     52.960  21.000   2.869  0.00919 **
PlotB1       -28.056     52.960  21.000  -0.530  0.60184
PlotB2       -26.111     52.960  21.000  -0.493  0.62710
PlotB3        -2.083     52.960  21.000  -0.039  0.96899
PlotB4        25.278     52.960  21.000   0.477  0.63808
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Correlation of Fixed Effects:
```

	(Intr)	PlotA2	PlotA3	PlotA4	PlotB1	PlotB2	PlotB3
PlotA2	-0.589						
PlotA3	-0.589	0.500					
PlotA4	-0.589	0.500	0.500				
PlotB1	-0.589	0.500	0.500	0.500			
PlotB2	-0.589	0.500	0.500	0.500	0.500		
PlotB3	-0.589	0.500	0.500	0.500	0.500	0.500	
PlotB4	-0.589	0.500	0.500	0.500	0.500	0.500	0.500

Graphical representation

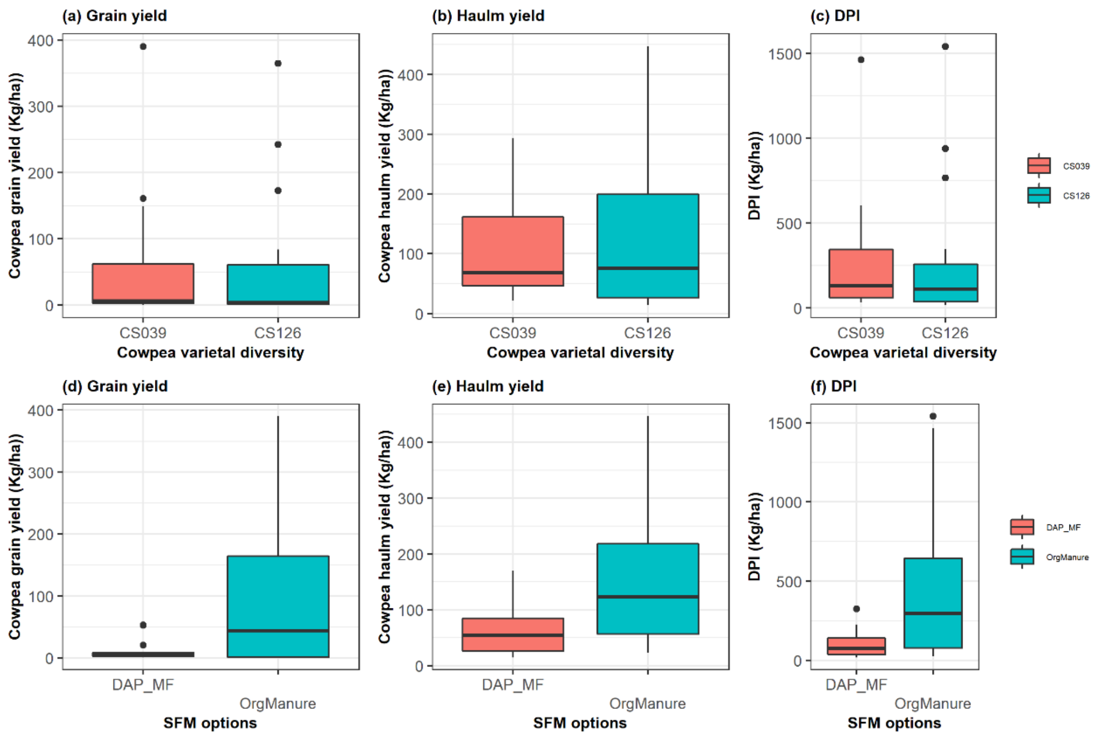


Figure 1: Overall AEI options effects of cowpea varietal diversity and SFM options

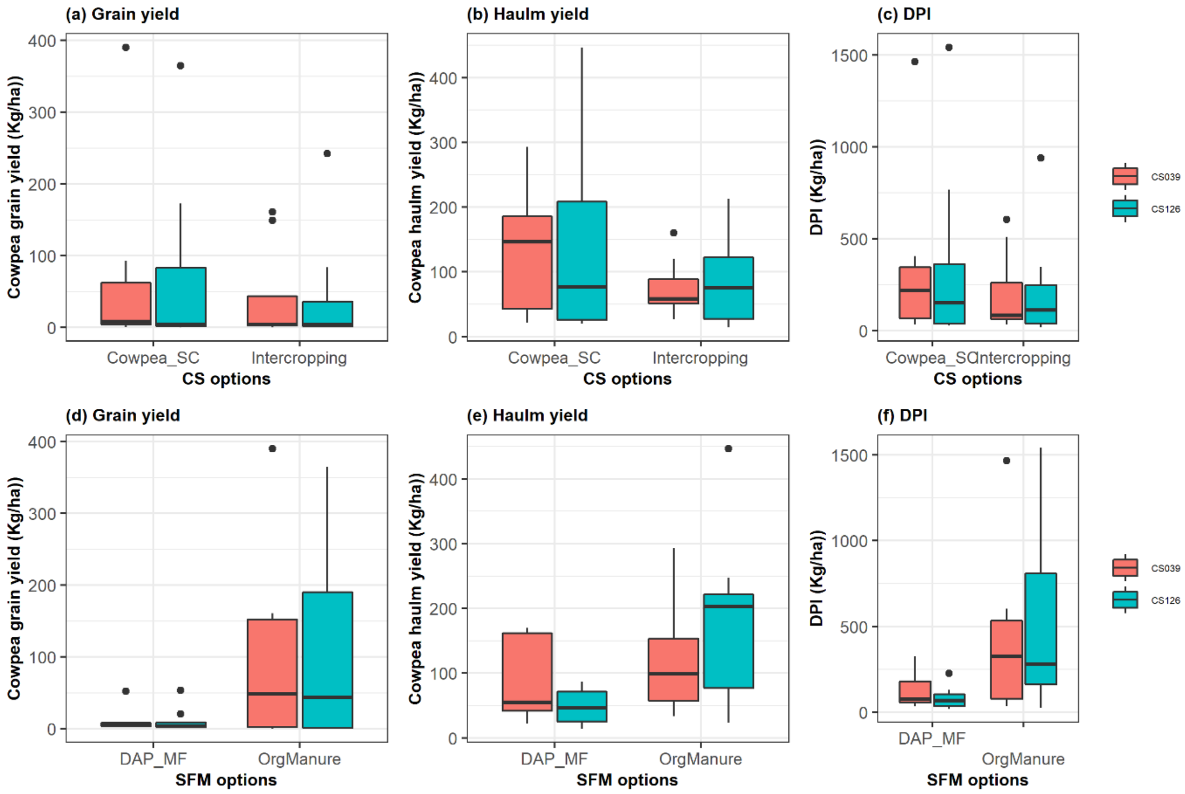


Figure 2: Overall AEI options effects of CS options and SFM options

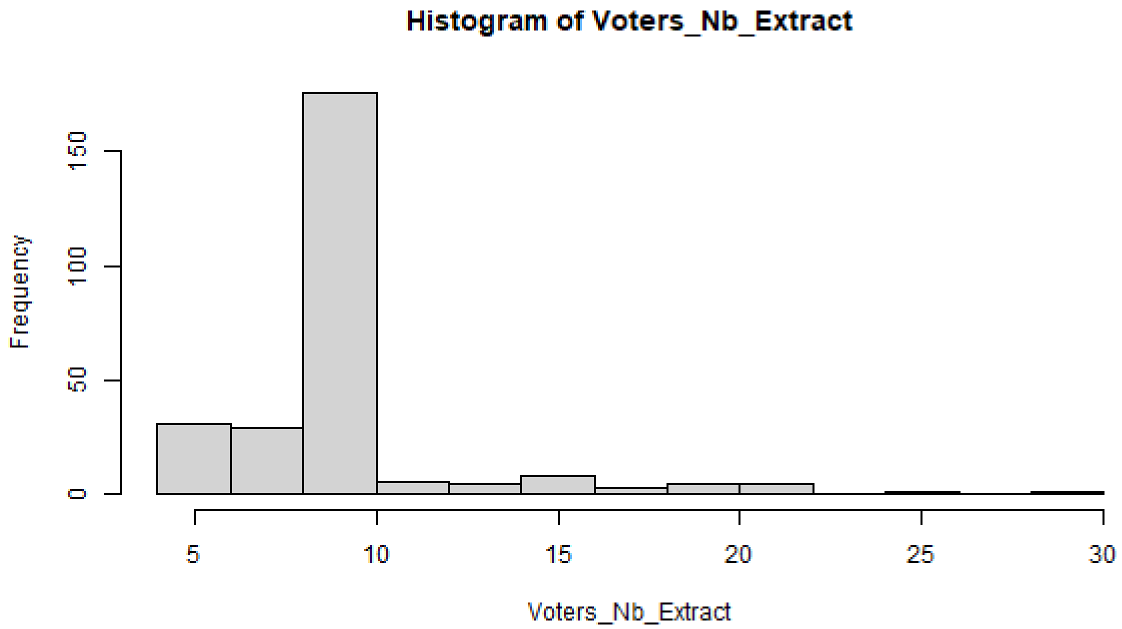
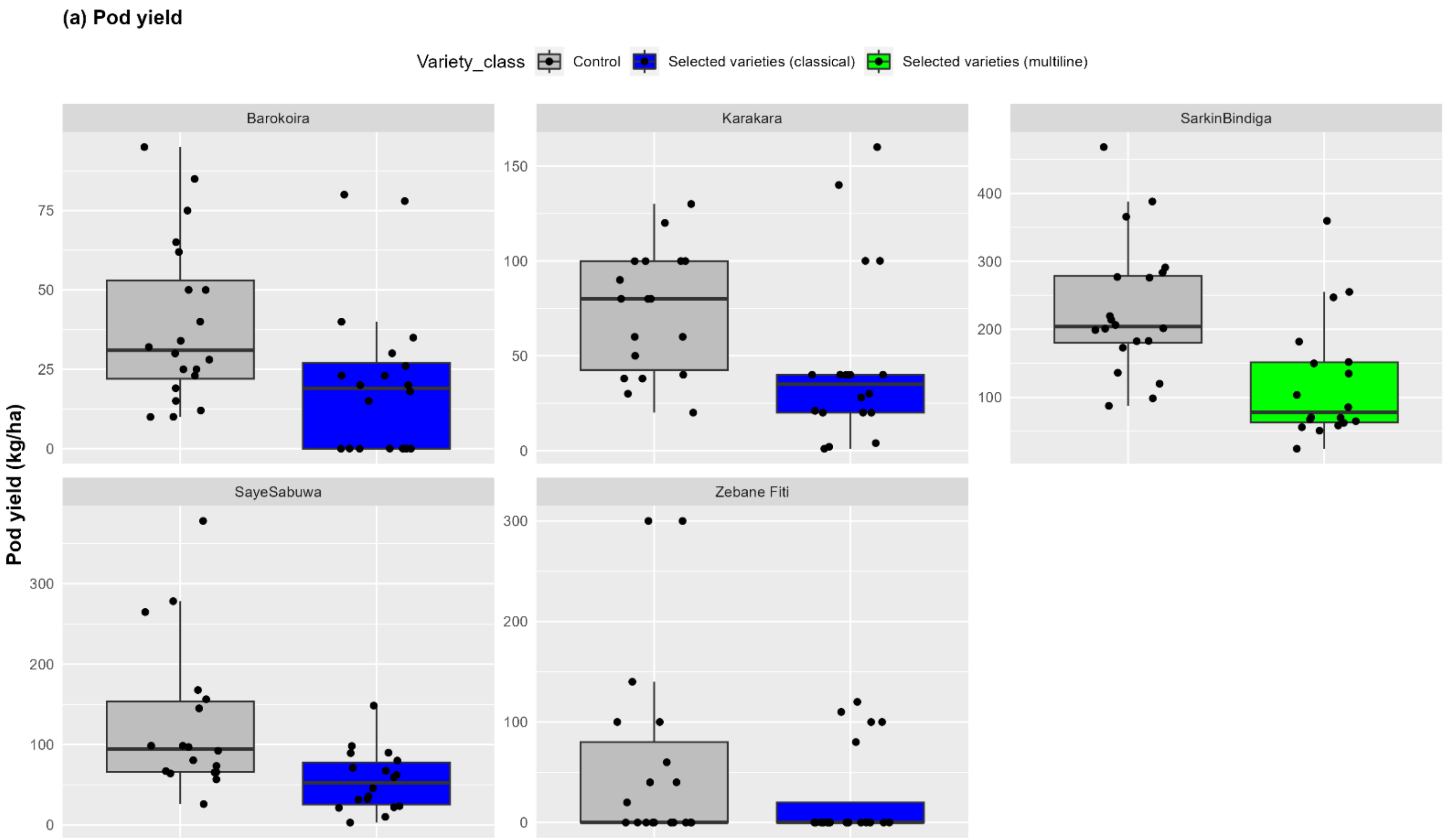


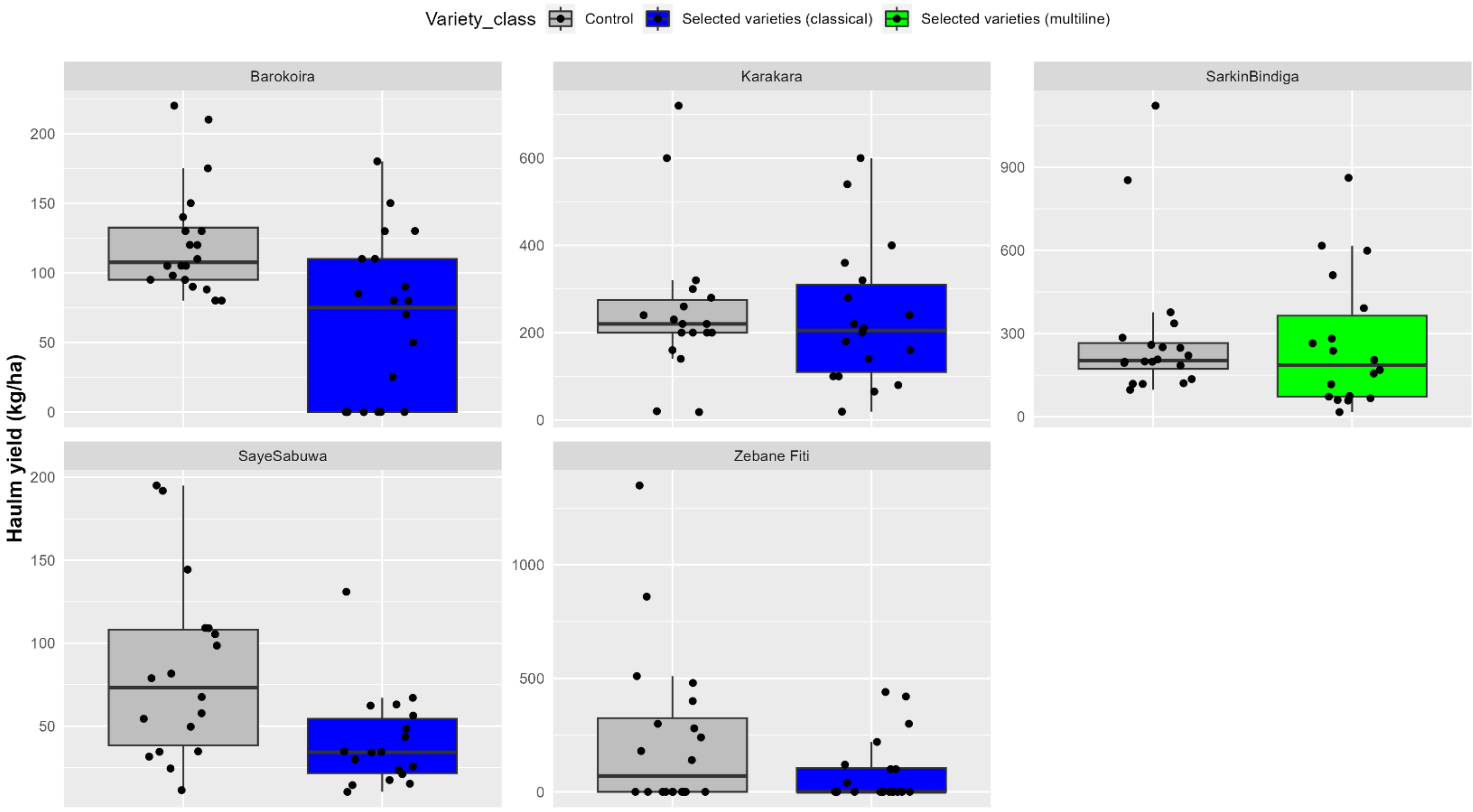
Figure 3: Distribution of farmers involved in the participatory assessment of the integrative trial

Annexe 3: Graphical representation where crop yields of the control varieties are higher than the selected one and Wicoxon test outputs for the decentralized trials of the dual-purpose cowpea varieties

A. Comparison of pod yield where the control varieties are higher than the selected varieties



(b) Cowpea Haulm yield



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B. Wicoxon test outputs for the decentralized trials of the dual-purpose cowpea varieties

Table 1: Detailed Wilcoxon test out for all the fifteen villages

Row highlighted in green shows that the selected cowpea varieties are significantly higher than the control varieties. Red means the opposite while the rows highlighted in white showed that there is no significant difference among the two types of the cowpea varieties.

Village	Trait	Median_CS	Median_Control	P-value	List_CS	List_Control
Arawraye	Pod_Yield	380.5	227	5.37×10^{-2}	c(CS012 = 20)	c(\`Bawchin jirgui\` = 1, \`Dan bauchi\` = 3, \`Dan gawgawa\` = 1, \`Dan jaho\` = 1, \`Gouchine zirgui\` = 1, \`IT90 (mai jan hanci)\` = 2, \`Koukan djirgui\` = 1, Lakkade = 3, \`Mai farine hantchi\` = 1, \`Mai hitila\` = 4, \`Mai yadiya\` = 1, \`Zizal zirgui\` = 1)
Arawraye	Haulm_Yield	1078	478.6	2.92×10^{-3}	c(CS012 = 20)	c(\`Bawchin jirgui\` = 1, \`Dan bauchi\` = 3, \`Dan gawgawa\` = 1, \`Dan jaho\` = 1, \`Gouchine zirgui\` = 1, \`IT90 (mai jan hanci)\` = 2, \`Koukan djirgui\` = 1, Lakkade = 3, \`Mai farine hantchi\` = 1, \`Mai hitila\` = 4, \`Mai yadiya\` = 1, \`Zizal zirgui\` = 1)
Arawraye	DPI	518	301.5	2.44×10^{-2}	c(CS012 = 20)	c(\`Bawchin jirgui\` = 1, \`Dan bauchi\` = 3, \`Dan gawgawa\` = 1, \`Dan jaho\` = 1, \`Gouchine zirgui\` = 1, \`IT90 (mai jan

						hanci)` = 2, `Koukan djirgui` = 1, Lakkade = 3, `Mai farine hantchi` = 1, `Mai hitila` = 4, `Mai yadiya` = 1, `Zizal zirgui` = 1)
Barokoira	Pod_Yield	19	31	2.29×10^{-2}	c(CS052 = 20)	c(`Doungouri koirey` = 6, `IT90 (mai jan hanci)` = 2, `Nina bi` = 2, `Nina kirey` = 5, Tchekole = 5)
Barokoira	Haulm_Yield	75	107.5	4.54×10^{-3}	c(CS052 = 20)	c(`Doungouri koirey` = 6, `IT90 (mai jan hanci)` = 2, `Nina bi` = 2, `Nina kirey` = 5, Tchekole = 5)
Barokoira	DPI	29.25	51.75	6.38×10^{-3}	c(CS052 = 20)	c(`Doungouri koirey` = 6, `IT90 (mai jan hanci)` = 2, `Nina bi` = 2, `Nina kirey` = 5, Tchekole = 5)
Boussaragui	Pod_Yield	207.5	200	0.94	c(`CWS-RIL-31-38-35` = 20)	c(`Dan Aloka` = 1, `Dan Illa` = 2, `Dan jan kudi` = 1, `Dan kourourou` = 1, `Dan zahi` = 1, `IT90 (mai jan hanci)` = 2, Lakkade = 10)
Boussaragui	Haulm_Yield	93	79	1	c(`CWS-RIL-31-38-35` = 20)	c(`Dan Aloka` = 1, `Dan Illa` = 2, `Dan jan kudi` = 1, `Dan kourourou` = 1, `Dan zahi` = 1, `IT90 (mai jan hanci)` = 2, Lakkade = 10)
Boussaragui	DPI	183.875	168.625	0.88	c(`CWS-RIL-31-38-35` = 20)	c(`Dan Aloka` = 1, `Dan Illa` = 2, `Dan jan kudi` = 1, `Dan kourourou` = 1, `Dan zahi` =

						1, `IT90 (mai jan hanci)` = 2, Lakkade = 10)
DaraAmadou	Pod_Yield	284.5	183.25	3.68×10^{-4}	c(`CWS-RIL-31-38-37` = 10, `CWS-RIL-31-38-46` = 10)	c(`Dan hadjia` = 3, `Dan izala` = 1, `Dan jaho` = 1, `Dan jan kudi` = 1, `Dan watsatsa` = 3, `Dan zahi` = 1, `IT90 (mai jan hanci)` = 10)
DaraAmadou	Haulm_Yield	555.15	398.5	1.68×10^{-4}	c(`CWS-RIL-31-38-37` = 10, `CWS-RIL-31-38-46` = 10)	c(`Dan hadjia` = 3, `Dan izala` = 1, `Dan jaho` = 1, `Dan jan kudi` = 1, `Dan watsatsa` = 3, `Dan zahi` = 1, `IT90 (mai jan hanci)` = 10)
DaraAmadou	DPI	332.2375	232.9875	1.97×10^{-4}	c(`CWS-RIL-31-38-37` = 10, `CWS-RIL-31-38-46` = 10)	c(`Dan hadjia` = 3, `Dan izala` = 1, `Dan jaho` = 1, `Dan jan kudi` = 1, `Dan watsatsa` = 3, `Dan zahi` = 1, `IT90 (mai jan hanci)` = 10)
Dembo	Pod_Yield	100	45	2.62×10^{-3}	c(CS127 = 20)	c(Boulibala = 2, `Doungouri kirey` = 2, `Doungouri koirey` = 10, Kirmitia = 6)
Dembo	Haulm_Yield	400	235	3.69×10^{-2}	c(CS127 = 20)	c(Boulibala = 2, `Doungouri kirey` = 2, `Doungouri koirey` = 10, Kirmitia = 6)
Dembo	DPI	168.75	112.5	7.17×10^{-3}	c(CS127 = 20)	c(Boulibala = 2, `Doungouri kirey` = 2, `Doungouri koirey` = 10, Kirmitia = 6)
DjindeMario	Pod_Yield	110	160	4.85×10^{-2}	c(CS001 = 20)	c(`Doungouri kassa` = 1, `Doungouri koirey` = 6, Gnagaou = 1, `IT90 (mai jan hanci)` = 1, KVX = 11)

DjindeMario	Haulm_Yield	780	370	4.63×10^{-2}	c(CS001 = 20)	c(`Doungouri kassa` = 1, `Doungouri koirey` = 6, Gnagaou = 1, `IT90 (mai jan hanci)` = 1, KVX = 11)
DjindeMario	DPI	310.625	200	0.14	c(CS001 = 20)	c(`Doungouri kassa` = 1, `Doungouri koirey` = 6, Gnagaou = 1, `IT90 (mai jan hanci)` = 1, KVX = 11)
GadeIya	Pod_Yield	253.3	294.1	0.35	c(`CWS-RIL-5-30-12` = 13, `CWS-RIL-5-30-2` = 1, `CWS-RIL-5-30-8` = 4, `CWS-RIL-5-30-9a` = 1, `CWS-RIL-5-30-9b` = 6)	c(Dandam = 1, `Hannun marini` = 10, Lakkade = 13, `Mai bakin kono` = 1)
GadeIya	Haulm_Yield	511.5	434.9	0.19	c(`CWS-RIL-5-30-12` = 13, `CWS-RIL-5-30-2` = 1, `CWS-RIL-5-30-8` = 4, `CWS-RIL-5-30-9a` = 1, `CWS-RIL-5-30-9b` = 6)	c(Dandam = 1, `Hannun marini` = 10, Lakkade = 13, `Mai bakin kono` = 1)
GadeIya	DPI	325.75	336.7	0.77	c(`CWS-RIL-5-30-12` = 13, `CWS-RIL-5-30-2` = 1, `CWS-RIL-5-30-8` = 4, `CWS-RIL-5-30-9a` = 1, `CWS-RIL-5-30-9b` = 6)	c(Dandam = 1, `Hannun marini` = 10, Lakkade = 13, `Mai bakin kono` = 1)
Karakara	Pod_Yield	35	80	4.27×10^{-2}	c(CS001 = 8, CS126 = 10)	c(`Babban wake mai harawa` = 6, `Babban wake mai lankwassa` = 5, `Da kanta uban diya` = 1, `Dan yagaou` = 4)
Karakara	Haulm_Yield	205	220	0.43	c(CS001 = 8, CS126 = 10)	c(`Babban wake mai harawa` = 6, `Babban wake mai lankwassa` = 5, `Da kanta

						uban diya` = 1, `Dan yagaou` = 4)
Karakara	DPI	63.75	127.5	0.13	c(CS001 = 8, CS126 = 10)	c(`Babban wake mai harawa` = 6, `Babban wake mai lankwassa` = 5, `Da kanta uban diya` = 1, `Dan yagaou` = 4)
Maiki	Pod_Yield	98.7	146.9	0.35	c(`CWS-RIL-31-38-3` = 20)	c(`Dan watsatsa` = 1, Dandam = 2, `IT90 (mai jan hanci)` = 1, Lakkade = 16)
Maiki	Haulm_Yield	135.5	112	0.11	c(`CWS-RIL-31-38-3` = 20)	c(`Dan watsatsa` = 1, Dandam = 2, `IT90 (mai jan hanci)` = 1, Lakkade = 16)
Maiki	DPI	114.575	144.0375	0.41	c(`CWS-RIL-31-38-3` = 20)	c(`Dan watsatsa` = 1, Dandam = 2, `IT90 (mai jan hanci)` = 1, Lakkade = 16)
Mayara	Pod_Yield	200	70	0.70	c(`CWS-RIL-31-38-35` = 20)	c(`Barta tatafi` = 1, `Dan gawgawa` = 2, `Dan izala` = 3, `Dan jan kudi` = 1, `Farin wake` = 5, `IT90 (mai jan hanci)` = 5, `Mai hitila` = 2)
Mayara	Haulm_Yield	70	20	3.16×10^{-3}	c(`CWS-RIL-31-38-35` = 20)	c(`Barta tatafi` = 1, `Dan gawgawa` = 2, `Dan izala` = 3, `Dan jan kudi` = 1, `Farin wake` = 5, `IT90 (mai jan hanci)` = 5, `Mai hitila` = 2)
Mayara	DPI	160	60	0.74	c(`CWS-RIL-31-38-35` = 20)	c(`Barta tatafi` = 1, `Dan gawgawa` = 2, `Dan izala` = 3, `Dan jan kudi` = 1, `Farin wake` = 5, `IT90 (mai jan hanci)` = 5, `Mai hitila` = 2)

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SarkinBindiga	Pod_Yield	78	204	7.62×10^{-5}	c(\`CWS-RIL-31-38-2\` = 2, \`CWS-RIL-31-38-20\` = 2, \`CWS-RIL-31-38-28\` = 1, \`CWS-RIL-31-38-49\` = 3, \`CWS-RIL-31-38-50\` = 7, \`CWS-RIL-31-38-7\` = 5)	c(Bahaushe = 3, Dandam = 6, \`Hannun marini\` = 5, Lakkade = 6)
SarkinBindiga	Haulm_Yield	187	203.25	0.10	c(\`CWS-RIL-31-38-2\` = 2, \`CWS-RIL-31-38-20\` = 2, \`CWS-RIL-31-38-28\` = 1, \`CWS-RIL-31-38-49\` = 3, \`CWS-RIL-31-38-50\` = 7, \`CWS-RIL-31-38-7\` = 5)	c(Bahaushe = 3, Dandam = 6, \`Hannun marini\` = 5, Lakkade = 6)
SarkinBindiga	DPI	106.9375	207.3	4.19×10^{-4}	c(\`CWS-RIL-31-38-2\` = 2, \`CWS-RIL-31-38-20\` = 2, \`CWS-RIL-31-38-28\` = 1, \`CWS-RIL-31-38-49\` = 3, \`CWS-RIL-31-38-50\` = 7, \`CWS-RIL-31-38-7\` = 5)	c(Bahaushe = 3, Dandam = 6, \`Hannun marini\` = 5, Lakkade = 6)
SayeSabuwa	Pod_Yield	52.5	94.65	1.04×10^{-3}	c(CS134 = 20)	c(\`Dan batsake\` = 1, \`Dan hadjia\` = 1, \`Dan jan kudi\` = 1, Dandam = 3, Lakkade = 14)
SayeSabuwa	Haulm_Yield	34.25	73.2	1.57×10^{-3}	c(CS134 = 20)	c(\`Dan batsake\` = 1, \`Dan hadjia\` = 1, \`Dan jan kudi\` = 1, Dandam = 3, Lakkade = 14)
SayeSabuwa	DPI	47.7625	88.675	6.7×10^{-4}	c(CS134 = 20)	c(\`Dan batsake\` = 1, \`Dan hadjia\` = 1, \`Dan jan kudi\` = 1, Dandam = 3, Lakkade = 14)
Tchake	Pod_Yield	143	143	0.24	c(CS133 = 7, \`CWS-RIL-31-38-35\` = 2, \`CWS-RIL-31-38-49\` = 2, \`CWS-RIL-31-38-52\` = 5, \`CWS-RIL-31-	c(\`Dan bauchi\` = 13, \`Dan watsatsa\` = 2, \`Mai hitila\` = 4)

					38-56` = 1, `CWS-RIL-31-38-6` = 3)	
Tchake	Haulm_Yield	72.5	46.75	0.16	c(CS133 = 7, `CWS-RIL-31-38-35` = 2, `CWS-RIL-31-38-49` = 2, `CWS-RIL-31-38-52` = 5, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-6` = 3)	c(`Dan bauchi` = 13, `Dan watsatsa` = 2, `Mai hitila` = 4)
Tchake	DPI	125.375	125.125	0.33	c(CS133 = 7, `CWS-RIL-31-38-35` = 2, `CWS-RIL-31-38-49` = 2, `CWS-RIL-31-38-52` = 5, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-6` = 3)	c(`Dan bauchi` = 13, `Dan watsatsa` = 2, `Mai hitila` = 4)
Warzou	Pod_Yield	106.6	65.1	0.14	c(`CWS-RIL-31-38-38` = 1, `CWS-RIL-31-38-39` = 1, `CWS-RIL-31-38-40` = 1, `CWS-RIL-31-38-41` = 1, `CWS-RIL-31-38-42` = 1, `CWS-RIL-31-38-43` = 1, `CWS-RIL-31-38-44` = 1, `CWS-RIL-31-38-45` = 1, `CWS-RIL-31-38-46` = 1, `CWS-RIL-31-38-47` = 1, `CWS-RIL-31-38-48` = 1, `CWS-RIL-31-38-49` = 1, `CWS-RIL-31-38-50` = 1, `CWS-RIL-31-38-51` = 1, `CWS-RIL-31-38-52` = 1, `CWS-RIL-31-38-53` = 1, `CWS-RIL-31-38-54` = 1, `CWS-RIL-31-38-55` = 1,	c(`Dan bauchi` = 11, `Dan jan kudi` = 1, `Dan tchabague` = 1, `Godosso mai bakin hanci` = 1, `Haoukan kowa` = 4, `IT90 (mai jan hanci)` = 1, `Mai tsanwayan diya` = 1)

					`CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-57` = 1)	
Warzou	Haulm_Yield	436.5	251.05	0.14	c(`CWS-RIL-31-38-38` = 1, `CWS-RIL-31-38-39` = 1, `CWS-RIL-31-38-40` = 1, `CWS-RIL-31-38-41` = 1, `CWS-RIL-31-38-42` = 1, `CWS-RIL-31-38-43` = 1, `CWS-RIL-31-38-44` = 1, `CWS-RIL-31-38-45` = 1, `CWS-RIL-31-38-46` = 1, `CWS-RIL-31-38-47` = 1, `CWS-RIL-31-38-48` = 1, `CWS-RIL-31-38-49` = 1, `CWS-RIL-31-38-50` = 1, `CWS-RIL-31-38-51` = 1, `CWS-RIL-31-38-52` = 1, `CWS-RIL-31-38-53` = 1, `CWS-RIL-31-38-54` = 1, `CWS-RIL-31-38-55` = 1, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-57` = 1)	c(`Dan bauchi` = 11, `Dan jan kudi` = 1, `Dan tchabague` = 1, `Godosso mai bakin hanci` = 1, `Haoukan kowa` = 4, `IT90 (mai jan hanci)` = 1, `Mai tsanwayan diya` = 1)
Warzou	DPI	170.625	86.875	0.5	c(`CWS-RIL-31-38-38` = 1, `CWS-RIL-31-38-39` = 1, `CWS-RIL-31-38-40` = 1, `CWS-RIL-31-38-41` = 1, `CWS-RIL-31-38-42` = 1, `CWS-RIL-31-38-43` = 1, `CWS-RIL-31-38-44` = 1, `CWS-RIL-31-38-45` = 1, `CWS-RIL-31-38-46` = 1, `CWS-RIL-31-38-47` = 1,	c(`Dan bauchi` = 11, `Dan jan kudi` = 1, `Dan tchabague` = 1, `Godosso mai bakin hanci` = 1, `Haoukan kowa` = 4, `IT90 (mai jan hanci)` = 1, `Mai tsanwayan diya` = 1)

					`CWS-RIL-31-38-48` = 1, `CWS-RIL-31-38-49` = 1, `CWS-RIL-31-38-50` = 1, `CWS-RIL-31-38-51` = 1, `CWS-RIL-31-38-52` = 1, `CWS-RIL-31-38-53` = 1, `CWS-RIL-31-38-54` = 1, `CWS-RIL-31-38-55` = 1, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-57` = 1)	
Zebane Fiti	Pod_Yield	0	0	9.19×10^{-2}	c(CS134 = 20)	c(`Doungouri Bero` = 1, `Doungouri koirey` = 9, Talhana = 4, `Wande mardje` = 3)
Zebane Fiti	Haulm_Yield	0	70	8.00×10^{-3}	c(CS134 = 20)	c(`Doungouri Bero` = 1, `Doungouri koirey` = 9, Talhana = 4, `Wande mardje` = 3)
Zebane Fiti	DPI	17.5	75	7.89×10^{-3}	c(CS134 = 20)	c(`Doungouri Bero` = 1, `Doungouri koirey` = 9, Talhana = 4, `Wande mardje` = 3)

Table 2: Detailed Wilcoxon test for the case studies of the selected cowpea varieties.

Village	CS_Variety	Trait	Median_CS	Median_Control	P-value	List_Control	N
Arawraye	CS012	Pod_Yield	380.5	227	0.05	c(\`Bawchin jirgui\` = 1, \`Dan bauchi\` = 3, \`Dan gawgawa\` = 1, \`Dan jaho\` = 1, \`Gouchine zirgui\` = 1, \`IT90 (mai jan hanci)\` = 2, \`Koukan djirgui\` = 1, Lakkade = 3, \`Mai farine hantchi\` = 1, \`Mai hitila\` = 4, \`Mai yadiya\` = 1, \`Zizal zirgui\` = 1)	11
Arawraye	CS012	Haulm_Yield	1078	478.6	2.92×10^{-3}		11
Arawraye	CS012	DPI	518	301.5	2.44×10^{-2}		11
Barokoira	CS052	Pod_Yield	19	31	2.97×10^{-2}	c(\`Doungouri koirey\` = 6, \`IT90 (mai jan hanci)\` = 2, \`Nina bi\` = 2, \`Nina kirey\` = 5, Tchekole = 5)	20
Barokoira	CS052	Haulm_Yield	75	107.5	4.54×10^{-3}		20
Barokoira	CS052	DPI	29.25	51.75	6.38×10^{-3}		20
Boussaragui	CWS-RIL-31-38-35	Pod_Yield	207.5	200	0.94	c(\`Dan Aloka\` = 1, \`Dan Illa\` = 2, \`Dan jan kudi\` = 1, \`Dan kourourou\` = 1, \`Dan zahi\` = 1, \`IT90 (mai jan hanci)\` = 2, Lakkade = 10)	8
Boussaragui	CWS-RIL-31-38-35	Haulm_Yield	93	79	1		8
Boussaragui	CWS-RIL-31-38-35	DPI	183.875	168.625	0.88		8
Dembo	CS127	Pod_Yield	100	45	2.62×10^{-3}	c(Boulibala = 2, \`Doungouri kirey\` = 2, \`Doungouri koirey\` = 10, Kirmitia = 6)	20
Dembo	CS127	Haulm_Yield	400	235	3.69×10^{-2}		20
Dembo	CS127	DPI	168.75	112.5	7.17×10^{-3}		20
DjindeMario	CS001	Pod_Yield	110	160	4.85×10^{-2}	c(\`Doungouri kassa\` = 1, \`Doungouri koirey\` = 6, Gnagaou = 1, \`IT90 (mai jan hanci)\` = 1, KVX = 11)	20
DjindeMario	CS001	Haulm_Yield	780	370	4.63×10^{-2}		20

DjindeMario	CS001	DPI	310.625	200	0.14		20
Maiki	CWS-RIL-31-38-3	Pod_Yield	98.7	146.9	0.35	c(`Dan watsatsa` = 1, Dandam = 2, `IT90 (mai jan hanci)` = 1, Lakkade = 16)	19
Maiki	CWS-RIL-31-38-3	Haulm_Yield	135.5	112	0.11		19
Maiki	CWS-RIL-31-38-3	DPI	114.575	144.0375	0.41		19
Mayara	CWS-RIL-31-38-35	Pod_Yield	200	70	0.70	c(`Barta tatafi` = 1, `Dan gawgawa` = 2, `Dan izala` = 3, `Dan jan kudi` = 1, `Farin wake` = 5, `IT90 (mai jan hanci)` = 5, `Mai hitila` = 2)	19
Mayara	CWS-RIL-31-38-35	Haulm_Yield	70	20	3.16×10^{-4}		19
Mayara	CWS-RIL-31-38-35	DPI	160	60	0.74		19
SayeSabuwa	CS134	Pod_Yield	52.5	94.65	1.045×10^{-3}	c(`Dan batsake` = 1, `Dan hadjia` = 1, `Dan jan kudi` = 1, Dandam = 3, Lakkade = 14)	18
SayeSabuwa	CS134	Haulm_Yield	34.25	73.2	1.57×10^{-3}		18
SayeSabuwa	CS134	DPI	47.7625	88.675	6.71×10^{-4}		18
Zebane Fiti	CS134	Pod_Yield	0	0	9.19×10^{-2}	c(`Doungouri Bero` = 1, `Doungouri koirey` = 9, Talhana = 4, `Wande mardje` = 3)	20
Zebane Fiti	CS134	Haulm_Yield	0	70	8.00×10^{-3}		20
Zebane Fiti	CS134	DPI	17.5	75	7.89×10^{-3}		20

Table 3: Detailed Wilcoxon test for the case studies of the most control cowpea varieties

Village	Control_Variety	Trait	Median_CS	Median_Control	P-value	List_CS	N
Barokoira	Doungouri koirey	Pod_Yield	0	56	3.12×10^{-2}	c(CS052 = 6)	6 6

Barokoira	Doungouri koirey	Haulm_Yield	0	140	3.12×10^{-2}		6
Barokoira	Doungouri koirey	DPI	0	82.5	3.12×10^{-2}		
Boussaragui	Lakkade	Pod_Yield	200	200	1	c(`CWS-RIL-31-38-35` = 10)	5
Boussaragui	Lakkade	Haulm_Yield	100	81	0.65		5
Boussaragui	Lakkade	DPI	180	169	1		5
DaraAmadou	IT90 (mai jan hanci)	Pod_Yield	253.5	192.15	3.90×10^{-3}	c(`CWS-RIL-31-38-37` = 4, `CWS-RIL-31-38-46` = 6)	10
DaraAmadou	IT90 (mai jan hanci)	Haulm_Yield	575.85	398.5	1.95×10^{-3}		10
DaraAmadou	IT90 (mai jan hanci)	DPI	329.725	245.9375	1.95×10^{-3}		10
Dembo	Doungouri koirey	Pod_Yield	100	45	9.20×10^{-2}	c(CS127 = 10)	10
Dembo	Doungouri koirey	Haulm_Yield	390	380	0.47		10
Dembo	Doungouri koirey	DPI	170	117.5	0.35		10
DjindeMario	Doungouri koirey	Pod_Yield	90	150	0.84	c(CS001 = 6)	6
DjindeMario	Doungouri koirey	Haulm_Yield	1100	310	0.24		6
DjindeMario	Doungouri koirey	DPI	380	182.5	0.31		6
GadeIya	Lakkade	Pod_Yield	220.5	274.1	0.33	c(`CWS-RIL-5-30-12` = 6, `CWS-RIL-5-30-8` = 3, `CWS-RIL-5-30-9b` = 4)	13
GadeIya	Lakkade	Haulm_Yield	491.2	455.9	0.54		13
GadeIya	Lakkade	DPI	294.2	326.15	0.49		13
Maiki	Lakkade	Pod_Yield	100	178.7	0.49	c(`CWS-RIL-31-38-3` = 16)	10

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Maiki	Lakkade	Haulm_Yield	179.25	120.5	0.55		10
Maiki	Lakkade	DPI	129.0875	187.7625	0.25		10
Mayara	IT90 (mai jan hanci)	Pod_Yield	300	80	0.62	c(`CWS-RIL-31-38-35` = 5)	5
Mayara	IT90 (mai jan hanci)	Haulm_Yield	70	20	0.10		5
Mayara	IT90 (mai jan hanci)	DPI	242.5	65	0.58		5
SarkinBindiga	Lakkade	Pod_Yield	103.5	159.6	6.25 x 10^{-2}	c(`CWS-RIL-31-38-20` = 1, `CWS-RIL-31-38-28` = 1, `CWS-RIL-31-38-49` = 1, `CWS-RIL-31-38-50` = 2, `CWS-RIL-31-38-7` = 1)	6
SarkinBindiga	Lakkade	Haulm_Yield	156	191.95	6.25 x 10^{-2}		6
SarkinBindiga	Lakkade	DPI	153	164.325	6.25 x 10^{-2}		6
SayeSabuwa	Lakkade	Pod_Yield	60.75	97.75	4.48 x 10^{-4}	c(CS134 = 14)	12
SayeSabuwa	Lakkade	Haulm_Yield	34.35	73.2	6.83 x 10^{-3}		12
SayeSabuwa	Lakkade	DPI	55.0875	95.525	9.76 x 10^{-4}		12
Tchake	Dan bauchi	Pod_Yield	156	131.5	0.84	c(CS133 = 3, `CWS-RIL-31-38-49` = 2, `CWS-RIL-31-38-52` = 4, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-6` = 3)	8
Tchake	Dan bauchi	Haulm_Yield	75.5	48.5	0.33		8
Tchake	Dan bauchi	DPI	135	114.3125	0.94		8
Warzou	Dan bauchi	Pod_Yield	96.5	54.3	0.37	c(`CWS-RIL-31-38-38` = 1, `CWS-RIL-31-38-39` = 1, `CWS-RIL-31-38-41` = 1, `CWS-RIL-31-38-44` = 1, `CWS-RIL-31-38-46` = 1, `CWS-RIL-31-38-52` = 1, `CWS-RIL-31-38-53` = 1, `CWS-RIL-31-38-54` = 1,	4
Warzou	Dan bauchi	Haulm_Yield	436.5	251.05	0.5		4
Warzou	Dan bauchi	DPI	170.625	86.875	0.5		4

						`CWS-RIL-31-38-55` = 1, `CWS-RIL-31-38-56` = 1, `CWS-RIL-31-38-57` = 1)	
Zebane Fiti	Doungouri koirey	Pod_Yield	0	10	1.34×10^{-3}	c(CS134 = 9)	8
Zebane Fiti	Doungouri koirey	Haulm_Yield	40	180	5.91×10^{-2}		8
Zebane Fiti	Doungouri koirey	DPI	25	97.5	2.2×10^{-2}		8

Annexe4: Questionnaire used for the baseline survey

ASSESSMENT OF AGROECOLOGICAL OPTIONS USED BY FARMERS TO ADDRESS PEDOCLIMATIC CONSTRAINTS ON FAMILY FARMS IN CENTRAL SOUTH AND WEST NIGER

This work is in the framework of the PhD thesis of SANI ISSA Mahaman Sanoussi (University of Sciences, Techniques and Technologies of Bamako (USTT-B) /IPR-IFRA, Mali; Wascal Programme; host laboratory: Unité Mixte de Recherche Diversité et Adaptation des Plantes, Université Dan Dicko Dankoulodo de Maradi, CowpeaSquare Project)

Semi-structured questionnaire for the farm survey

N° of the form : ………….

Date:……………………………………………………… ……

Region Maradi □, Dosso □, Tillabery □

Village : □**, Zébano fiti** □, **Kaboye_Koira** □, **Karakara** □, **Tchaké** □**,** , **Saé Saboua** □**, Gade Iya** □

Section 1: Information of the respondants in the family farm (FF)

Name of the head of the FF : ……………………………………….

Farmer's ID of the head of the FF (CowpeaSquare): …………………………………

Farmers' federations: FUMA-Gaskiya □, Mooriben □

Farmers' organisation : ……………………………..

Sex: Male □ Fema,e□

Age :………..

Marital statut: Single □ Maried□ widow □ Divorced□

Number of spouses (for men) :

Number of Kids:

Main source of income: Agriculture □– Animal husbandry□ – Trading □ – Craft □– Government service □– Other (Precis) □

Second source of income: Agriculture □– Animal husbandry□ – Trading □ – Craft □– Government service □– Other (Precis) □

Section 2: Family farm characteristics

1.1. Is there presence of main field in the FF (**Gandu**)? Yes; No

1.2.Is there presence of main field led by the female (WF) in the FF? Yes;

1.3. If not, why?

1.4.What is the name, meaning, distance, location and the size of both of the two fields?

Type of the fields	**Name of the field**	**Meaning of the field's name**	**Distance (km) from the village to this field**	**Location of the field**	**Estimated area/size of the field (ha)**
Main field					
Female field (WF)					

1.5.Main crop species, management practices and sol types in the main field

1.5.1. What are the main crop species cultivated in of the field type? Provide the grain yield obtained in the last three years.

Fields	2021		2020		2019	
	Crop specie	**Estimated grain yield (kg/ha)**	Crop specie	**Estimated grain yield (kg/ha)**	Crop specie	**Estimated grain yield (kg/ha)**
Main field						
Field led by female						

1.5.2. What is the most preferred intercropping pattern you use in each of the two field types?

Field types	**Intercropping type**	**Explain the reasons why you prefer using this type**
Main field		
Female field		

1.6.What are the crop management practices you use for these main crop species in each of the field type?

Type of the fields	Crop Management practices	Pearl millet	Sorghum	Cowpea	Groundnut	Sesame	Other
Main field	Soil fertilization: How do you apply organic and mineral fertilizer in the main field?						
	Tillage: Minimum tillage or deep tillage?						
	Sowing methods						
	Transplanting						
	Harvest methods						
	Pest and diseases control: What are the products you use to control these?						
	Other						
Female field	Soil fertilization: How do you apply organic and mineral fertilizer in the main field?						
	Tillage: Minimum tillage or deep tillage?						
	Sowing methods						
	Transplanting						
	Harvest methods						

	Pest and diseases control: What are the products you use to control these?						
	Other						

1.7.Information on the soil types.

	Name of the soil type in the local language	**Texture (sandy, loamy, clay)**	**Level of fertility: Very fertile, fertile, poor, very poor**
Main field			
Female field			

1.8.Indicate for each type of the livestock, the number of heads you use in your field for your activities and/or as sources of manure used in the field and/or for composting

Types	**Number**
Cattle	
Goats	
Sheep	
Donkey	
Camel	
Horse	

Section 3: Farmers perceived key drivers hindering crop productivity and the main agroecological intensification options (AEI) practiced in the family farms

2.1.What are the key drivers related to soil you have been observing in your field?

Tick the good response and write down the possible constraints cited by farmers.

Soil constraints	**Present? (Yes/No)**	**Describe, comment**
Water erosion		
Wind erosion		

Soil acidification		
Soil leaching		
Soil crust		
Soil fertility decrease		
Other		
Other		
Other		

2.2. What are the rainfall uncertainties you have been observing in the field?

Rainfall uncertainties	**Present? (Yes/No)**	**Describe, comment**
Recurrent drought events		
Increase of flood frequency		
Late onset of the rainy season		
Increase of dry spells frequency		
Insufficient rainfall amount		
Other		
Other		
Other		

2.3. What are the socio-economic drivers you observe in the FF?

Socio-economic drivers	**Present? (Yes/No)**	**Describe, comment**
Low purchasing capacity of farmers		
Rapid population growth		
Crop residues export from the fields		
Low access to climatic information		
Inadequacy of the extension service system		
Limited access to markets		
Continuous use of outdated farming tools		
Other		
Other		

Other		

2.4. For the past rainy season, what agroecological intensification options did you use to increase agricultural production?

a. In the main field and for the past rainy season, which options did you use?

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Among these options you have mentioned, which ones do you use most in this type of field?

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b. And for the female field, which options did you use?

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Among these options you have mentioned, which ones do you use most in this type of field?

....
....
....
....

2.5. What is the historical background and performance (incidence) of agroecological intensification options on your family farms?

Level of satisfaction of the practice: 0. Option never tested by the farmer. **1**. I am not satisfied. **2**. Satisfied. **3**. Very satisfied.

A. In the main field

List of AEI options	**Details of the practice: e.g.: type of compost, biopesticide**	**Origin of the practice: Name of the project? E local BBnitiative?**	**Since when, you practice it?**	**Reason for adoption**	**Level of application (% of the field used for the practice, if any)**	**Level of satisfaction**	**Factors limiting the deployment of this practice?**

Compost							
Biopesticide: botanical pesticide							
Biological pest control							
Intercropping							
Crop rotation							
Seed balls (ashes)							
Seed balls (NPK)							
Micro-dosing fertilizer							
Organic manuring							
FMNR							
OGA: hygienic human urine as organic fertilizer							
Zai							
Half moon							
Stone bridge							
Mulching							
Use of cover plants							
Transplanting							

Minimum tillage							
Use of new varieties tolerant to drought							
Use of new varieties resistant to pest and diseases							
Other							
Other							

B. For the female field

List of AEI options	**Details of the practice: e.g.: type of compost, biopesticide**	**Origin of the practice : Name of the project ? e local initiative?**	**Since when, you practice it?**	**Reason for adoption**	**Level of application (% of the field used for the practice, if any)**	**Level of satisfaction**	**Factors limiting the deployment of this practice?**
Compost							
Biopesticide: botanical pesticide							
Biological pest control							
Intercropping							
Crop rotation							
Seed balls (ashes)							
Seed balls (NPK)							

Micro-dosing fertilizer							
Organic manuring							
FMNR							
OGA: hygienic human urine as organic fertilizer							
Zai							
Half moon							
Stone bridge							
Mulching							
Use of cover plants							
Transplanting							
Minimum tillage							
Use of new varieties tolerant to drought							
Use of new varieties resistant to pest and diseases							
Other							
Other							

2.6. Would you be interested in working with us (in the framework of the thesis and associated projects) to strengthen the sustainability of your practices? Yes, or No?

2.7. How do you foresee our future collaboration (list your propositions)?

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
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2.8.What are you overall remarks?

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Observations or remarks of the surveyor:

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……………………………………………………………………………………………
…………………………………………………………………………………………….

Geographic coordinates (Compulsory)

Altitude………………………Longitude………………………………Latitude……………
………………………

Name and signature of the surveyor