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Comparison of three groundnut varieties in the sub-Saharan Africa: yield, crop diseases and symbiotic interactions with soil microorganisms

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Abstract:

To enhance groundnut yields in Senegal, research generated technical proposals. However, a systemic perspective is necessary to assess their performance within the context of farmers' fields. We evaluated three short-cycle groundnut varieties—Fleur 11, 55-33, and 55-437—on two farmers' fields with different soil fertility levels, and considering two levels of mineral fertilization and rhizobial inoculation. The trials were conducted in 2018, a year characterized by a prolonged rainfall break during the vegetative phase of the crop. Varieties 55-33 and 55-437 achieved half of their potential yield, while Fleur 11 achieved only one-quarter. The Fleur 11 variety was significantly affected by fungal diseases, leading to seedling mortality and pod rot, particularly on the less fertile field. The effect of fertilizer application on yields was minimal in the least fertile field. With an average of 114 nodules per plant, the varieties demonstrated a good nodulation capacity, indicating that biological nitrogen fixation was potentially significant. Fertilizer application enhanced nodulation, suggesting that nutrient availability, especially phosphorus, was a limiting factor for symbiotic nitrogen fixation in these agroecosystems. Mycorrhization was intense, especially in the least fertile soil. Bacterial inoculation showed not effect on the measured variables. Stepwise regression analysis revealed that variability in seed yield was primarily associated with soil carbon content and crop damages from soil-borne diseases, whereas fodder yield was mainly linked to the number of nodules per plant. Although often overlooked in current crop models, soil-borne diseases represent a major barrier to improving groundnut yields. Symbiotic interactions with soil organisms appear to be of critical importance in the studied agroecosystems. Combining diseases resistance, strong potential symbiosis with soil microbes, and a favorable response of fertilizer, varieties 55-33 and 55-437 are valuable options for enhancing the productivity and resilience of groundnut crops in marginal environments.

Keywords: agronomic diagnosis, fertilization, inoculation, mycorrhization, nodulation, pests, cropping

1. Introduction

Researchers in Senegal suggested technical improvements for groundnut (*Arachis hypogaea L.*) yield performance, including different crop varieties (Faye et al., 2022), mineral fertilization (Faye et al., 2016), and inoculation with nitrogen-fixing bacteria and mycorrhizal fungi (Sene et al., 2023; Zaiya et al., 2018). Notable varieties listed in the ECOWAS-UEMOA-CILSS (2017) catalogue include 55-33, 55-437, released in 1955, and Fleur 11, released in 1995. These have a short cycle of about 90 days and are still employed by farmers despite new, more efficient varieties proposed by breeders (Faye et al., 2022). Technical data sheets advise on using N-P-K fertilizer formula 6-20-10 at 150 kg ha^{-1} applied between 10- and 15-days post-sowing, alongside fungicide and insecticide treatments. Recommended strains for inoculation come from roots and nodules isolated from Senegalese soils, to be mixed with peat or applied as a liquid during sowing (Zaiya et al., 2018).

However, only few farmers adopted these technical proposals on (Faye et al., 2019). Farmers typically use their own untreated seeds, with minimal pesticide and mineral fertilizer use, and limited organic amendments. Groundnut cultivation is commonly integrated into a two-year rotation with millet (Pennisetum glaucum L.) or, less frequently, a three-year rotation including fallow. The low adoption rates of new techniques are due to several factors: the high cost and limited availability of essential inputs like fertilizers and certified seeds, difficulties in obtaining inoculants, and the generally low profitability of groundnut cultivation. Moreover, the effectiveness of these technical proposals, often assessed in controlled experimental settings, can differ significantly under actual farm conditions, further discouraging their uptake.

To evaluate the varieties used by farmers and identify any limiting factor for their performance, a systemic analysis is crucial, one that considers the intricate interactions between varieties, technical choices, soil and crop components. This approach as shown by Tounkara et al. (2020), facilitates the regional extrapolation of plot-level data. Furthermore, it allows for the identification and quantification of how various technical combinations influence groundnut-soil symbiotic relationships. These relationships encompass bacterial nitrogen fixation (Zhang et al., 2023), enhanced nutrient and water efficiency through mycorrhizal fungi (Ndeko et al., 2023; Pawar et al., 2018), and the suppression of soilborne diseases by beneficial organisms (Woo et al., 2022). Notably, in low-input agricultural systems, these symbiotic relationships could be pivotal for both production and climate change resilience (Liu et al., 2023).

The aims of this study were: 1) to compare the yield performance of different groundnut varieties under varying soil fertility levels, with and without mineral fertilization, and with and without inoculation with symbiotic bacteria 2) to evaluate how different groundnut varieties establish symbiotic relationships with soil microorganisms under these varying cultivation methods, and 3) to identify key environmental and crop indicators that significantly influence groundnut yield.

2. Materials and methods

2.1. Study site

This research was conducted in Diohine (14º30'4"N and 16º30'10"W), a village within the Population Health Environment Observatory (OPSE) of Niakhar, managed by the IRD. The village is located in the Fatick administrative region, situated in the central western part of Senegal's groundnut basin (Delaunay et al., 2018) (Figure 1). Diohine is part of the Sudano-Sahelian zone, receiving an average annual rainfall of 590 mm over the past five years. The majority of this precipitation occurs between July and October, which constitutes the sole growing season for groundnuts and millet. The arenosol soils in the area are characterized by their sandy texture and typically low nutrient content. The home areas are clustered together, with cultivated plots distributed around them (Figure 1). Soil fertility in cultivated areas decreases progressively with increasing distance from home areas, due to the diminishing input of organic matter.

Plots located close to the village, referred to as "Homefields," are cultivated annually with millet and receive regular inputs of organic matter from household waste and transhumant animals returning to the village during the dry season. In contrast, more distant plots, known as "bush fields," are often engaged in crop rotations involving millet and groundnuts. These distant plots receive fewer organic matter inputs, resulting in reduced soil fertility. A specific three-year rotation that includes fallow periods is practiced on the most distant plots. Farmers collectively agree to fallow these plots simultaneously, allowing for the maintenance of a minimum number of livestock in the village during the rainy season. Grazing pressure on these fallows is minimal. Soil fertility levels are often lowest on these more distant plots (Tounkara et al., 2020).

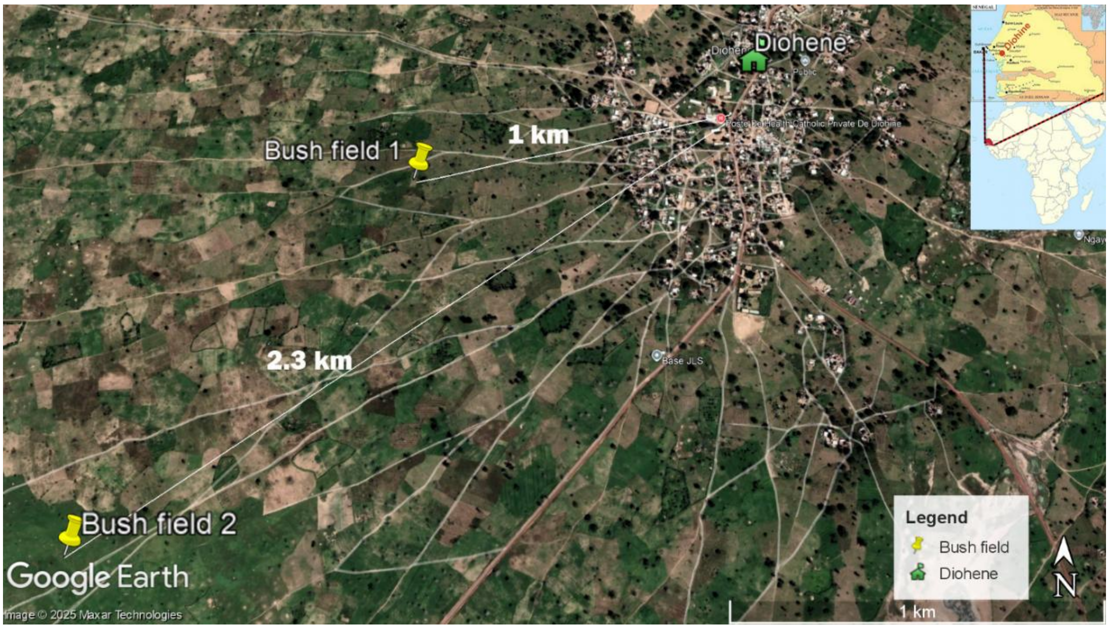

Figure 1: Geographical location of the study area and trial fields

2.2. Groundnut trial set-up

In 2018, two groundnut trials were conducted on two farmers' plots with differing levels of soil fertility. The first plot (BF1), a bush field, received moderate manure input and is about 1 km from the village with a millet/groundnut rotation. The second plot (BF2), also a bush field, located 2.3 km the furthest from the village received minimal manure and follows a three-year rotation (millet/groundnut/fallow) (Figure 1).

Each trial (BF1 and BF2) comprised four blocks or replications with the following factorial combinations (Photo 1a b):

- A variety factor (Var) with three types: Fleur 11, 55-33, and 55-437
- A fertilization factor (F) with two types: without and with mineral fertilization providing 150 kg ha-1 of NPK fertilizer with a formula of 6-20-10
- An inoculum factor with two types: without and with a mixture of local nitrogen-fixing bacterial strains (ISRA400, ISRA422, ORS3257, and ORS3409) as described by Zaiya et al. (2018)

Not all combinations of the three factors were tested. The effect of rhizobial inoculation was examined only on variety 55-437 and variety Fleur 11, excluding variety 55-33 and the fertilized treatments, reducing the number of treatments to 8 instead of 12. Certified seeds for each variety were provided by the Centre de Recherches Agricoles (CRA) of the city of Saint-Louis, for varieties 55-33 and 55-437, and by the “Centre d'Étude Régional pour l'Amélioration de l'Adaptation à la Sécheresse” (CERAAS) in the city of Thiès, for variety Fleur 11. A pre-sowing germination test indicated germination rates of 95% ± 4.5 for each variety. Groundnuts were sown following the first significant rainfall on 30 June 2018, at a density of 130,000 plants per hectare with 15 cm spacing between plants and 50 cm between rows across all varieties. Each elementary plot covered 20 m^2, comprising 10 rows of seedlings, each 5 meters long (Photo 1b). The formula and dose of mineral fertilizer were determined based on the Senegalese Institute of Agricultural Research (ISRA) recommendations for this region of the groundnut basin (Faye et al., 2019). Fertilizer application occurred 30 days post-sowing along the groundnut rows (Photo 1a). Inoculation was conducted at sowing using a liquid inoculant prepared according to the method described by Zaiya et al. (2018) and applied to the sowing furrow. No pesticides were applied to the seeds. Manual weeding was performed at 30 and 45 days after sowing, and harvesting occurred 120 days post-sowing.

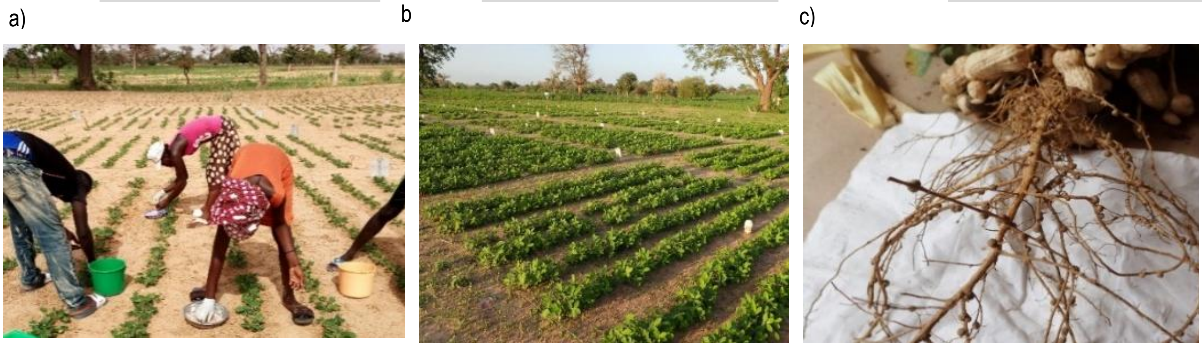

Photo 1 a b c: Some photos of the trials. a: Mineral fertilizer application; b: Experimental set-up; c: Groundnut root nodules (photo credit: Sophie Djiba)

2.3. Variables collected

Table 1 presents the collected variables and the measurement methods used. These variables are classified into three categories: 1) Variables characterizing the physico-chemical environment, including rainfall, apparent soil density, soil chemical analyses at groundnut sowing, and soil water status during different periods of the crop cycle; 2) Variables characterizing the symbiotic interactions of the crop with soil organisms, including the frequency and intensity of root mycorrhization and the number and weight of groundnut nodules; 3) Variables characterizing crop functioning, including biomass at flowering, yield and its components, crop diseases, and amounts of nitrogen and phosphorus absorbed at harvest.

2.4. Statistical analysis

Statistical analyses were conducted using STATISTICA 8.0, StatSoft, Inc. 2007. Multifactor analyses of variance were employed to determine the effects of the studied factors and their interactions on the measured variables. When significant treatment effects were observed, comparisons of the associated means were performed at a 5% probability threshold using the Newman-Keuls test. Linear regressions of seed and haulm yields were subsequently undertaken utilizing the least correlated measured variables in the dataset as potential explanatory variables. This analysis resulted in the selection of carbon and pH among the soil chemical characterization variables, and the retention of only the mortality rate of seedlings and pods attacked by fungi among the fungal disease characterization variables. Soil apparent densities were considered indicative of differences in soil water dynamics observed during the cycle, with lower apparent densities being less conducive to rainwater infiltration compared to higher apparent densities. Mycorrhization intensities were used rather than frequencies due to their greater sensitivity to treatments. Similarly, the number of nodules was chosen over weight, which exhibited high correlation.

Table 1: Methodology for collecting variables on the groundnut trials. N= number of observations

Variables	Measurement methods	N
Soil and climate	Chemical characterization: laboratory analysis of composite soil samples taken from the 0-10 cm horizon before sowing groundnuts (C, N, P Olsen, K, Mg, CEC and pH). Analyses carried out at LAMA (https://imago.ird.fr/moyens-analytiques/dakar).	64
	Bulk density (g cm^{-3}): Soil samples were taken from horizons 0-10; 10-20 and 20-30 cm deep and weighed after drying for 72 h at 105°C. This measurement was repeated at 3 points per treatment. Apparent density = dry weight of soil / volume of sampling cylinder.	64
	Rainfall was recorded during the season and water balances were calculated for each period of the groundnut development cycle by the difference between rainfall and potential evapotranspiration (P-EPT). Evapotranspiration was calculated using meteorological data using the Penman-Monteith equation	2
	Measurement of relative soil humidity at a frequency of 15 days during the cycle. Measured using a Diviner 2000 probe on 24 160 cm tubes installed on all the treatments in the 3 blocks of each trial.	48

Symbiotic soil/plant interactions	Number and biomass of plant nodules^{-1} (after drying at 65° for 48 h) measured on 5 successive plants per treatment taken at a depth of 50 cm 60 days after sowing.	64
	Mycorrhization frequency and intensity: Sampling of fine roots from 3 plants/treatment 60 days after sowing groundnuts. Rinsing and staining of the roots and microscopic observation (×250) of the stained root fragments, then calculation of the variables (method of Trouvelot et al. (1986)).	64
Plants functionning	Plant density (number of plants treated^{-1}) and seedling damping-off rate (% of ungerminated seeds) estimated 10 days after emergence.	64
	Biomass of haulm at 60 days after sowing estimated on 5 plants per treatment after drying at 65°C for 48 hours	
	Number of pods plant^{-1} estimated after collecting all the pods on the 5 plants previously used for estimating the biomass of the haulm at flowering.	
	Pods and tops collected from 20 plants per treatment at the end of the cycle and weighed after drying at 65°C for 48 h. Measurement of yield components: number of seeds m^2, number of pods m^2 and weight of 100 seeds.	
	Sorting of immature pods, pods attacked by fungi, iules and termites. Estimation of the percentage of each category of pod in relation to the total number of pods.	

3. Results

3.1. Rainfall and soils were particularly unfavorable for production

In 2018, rainfall occurred from June to October, totaling 477 mm, which was unevenly distributed between the vegetative and reproductive phases of the groundnut crop. The water balance (Rainfall-Potential EvapoTranspiration) was negative (-17 mm) during the vegetative phase but positive during the formation (+121 mm) and pod-filling (+87 mm) phases (Figure 2). These study conditions allowed for the evaluation of agricultural techniques in a climatic scenario typical of the driest years, as 2018 was in the first quartile (476 mm) of the recorded series from 2000 to 2020 at Bambey station (14°42'N, 16°28'W). Soil chemical parameters at groundnut sowing indicated that the soil in the trial area closest to dwellings (BF1) was generally more fertile than that further away (BF2) (Table 2). Soil bulk density to a depth of 30 cm was significantly higher in BF2 compared to BF1 (Table 2). Soil moisture profiles showed an accumulation of water in both areas between 44th and 63th days after sowing, followed by a regression. This accumulation was lower in BF2 (not shown).

Table 2: Physico-chemical soil characteristics at groundnut sowing in 2018. BF1: bush field 1; BF2 bush field 2. Soil chemical characteristics were analyzed on the 0-10 cm horizon.

Factor	pH water	C%	N (%)	P Olsen (mg kg^{-1})	K (cmol 100g^{-1})	Mg (cmol 100g^{-1})	CEC (cmol 100g^{-1})	Bulk density at 0-30 cm (g cm^{-3})
BF1 (close to dwellings)	6.64 ± 0.03 a	0.51 ± 0.01 a	0.04 ± 0.00 a	2.39 ± 0.15 a	0.24 ± 0.01 a	0.41 ± 0.01 a	1.34 ± 0.02 a	1.57 ± 0.00 b
BF2 (far from dwellings)	6.52 ± 0.03 b	0.34 ± 0.01 b	0.03 ± 0.00 b	1.51 ± 0.09 b	0.21 ± 0.01 b	0.34 ± 0.01 b	0.90 ± 0.01 b	1.64 ± 0.00 a
Number of observations	64	64	64	64	64	64	64	576
Pr > F	**0.01**	**<0.00**	**<0.00**	**0.00**	**0.01**	**0.00**	**<0.00**	**<0.00**

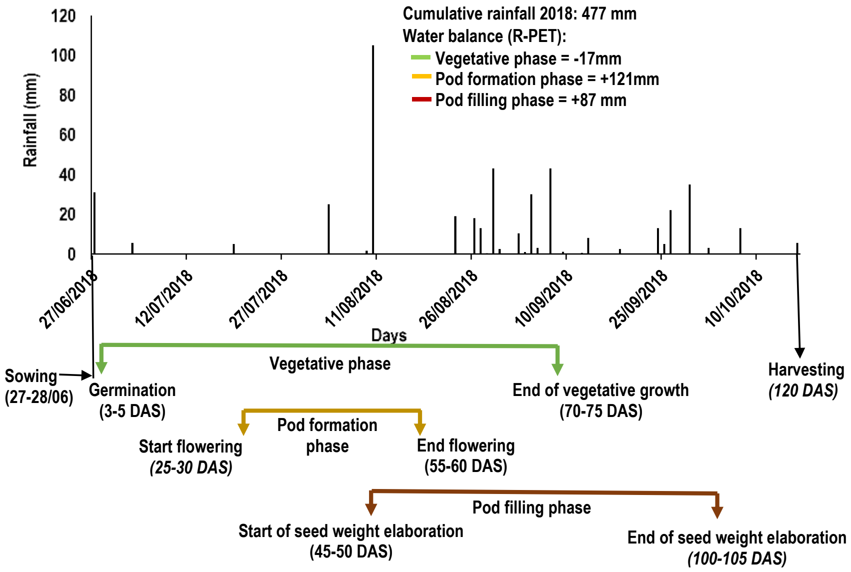

Figure 2: Distribution of rainfall during the different phases of the groundnut cycle in 2018. DAS: number of days after sowing

3.2. Variety and susceptibility to soil-borne diseases were key factors determining yield variability.

Groundnut variety yields ranged from 0.7 to 1 t ha-1 for seeds and from 1.6 to 1.8 t ha-1 for haulms. The Fleur 11 variety exhibited the lowest seed and haulm yields across all field types and fertilization conditions. Notably, these yields were significantly higher in BF1 compared to BF2. The application of mineral fertilizer had a positive effect on both seed and haulm yields; however, this significance was limited to varieties 55-33 and 55-437 due to early seedling mortality. On the 15th day post-sowing, plant densities for Fleur 11 were lower than those for varieties 55-33 and 55-437, with only 52% of sown seeds developing into mature plants for Fleur 11, in contrast to rates exceeding 90% for varieties 55-33 and 55-437. Specifically, seedling mortality for Fleur 11 was notably high in BF2. Additionally, the rate of immature pods was twice as high in the less fertile soil of BF2, and incidences of fungal, Myriapoda (iules), and termite attacks were substantially greater. Fleur 11 was more susceptible to these attacks relative to other varieties, with fungi such *as Aspergillus niger*, *Aspergillus parasiticus*, and *Rhizoctonia solani* identified on infested groundnut pods. Higher rates of immature and diseased pods correlated with elevated seedling mortality rates. Yield component relationships underscored the critical role of plant density per m^{-2} in influencing pod number per m^{-2} and overall seed yield (Figure 3 a, b). In BF2, increased post-flowering water stress resulted in decreased 100-seed weight yield components compared to BF1 (Figure 3 c). Stepwise linear regression analysis identified seedling mortality rate, fungal pod attack rate, and soil carbon content as significant predictors of groundnut seed yield under the study's conditions. For haulm yield, the number of nodules per plant emerged as the primary predictor (Table 4).

Table 3: Yield, plant density (indicator of % dead seedlings), immature pod rate and diseased pod rate in the different treatments. BF1 and 2: bush field 1 and 2; F0: without fertilizer; F1: fertilizer; NS: not significant *($p>0.05$)*. Non-significant interactions are not detailed.

Factors		**Seed yield (t ha^{-1})**	**Haulms yield (t ha^{-1})**	**Plant density (ind $m^{(-)2}$)**	**Rate of immature pods (%)**	**Rate of pods attacked by fungi. iules and termites (%)**
Field type (BF)	BF1 (close to dwellings)	1.30 ± 0.1 a	2.18 ± 0.1 a	11 ± 0.4	13.5 ± 0.7 b	9.9 ± 0.9 b
	BF2 (far from dwellings)	0.51 ± 0.0 b	1.31 ± 0.1 b	9 ± 0.6	26.7 ± 1.7 a	18.7 ± 1.5 a
	Pr > F	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Variety (Var)	Fleur11	0.66 ± 0.1 b	1.65 ± 0.1 b	6 ± 0.4 b	22.02 ± 2.89	17.4 ± 2.2 a
	55-33	1.01 ± 0.1 a	1.73 ± 0.1 a	12 ± 0.3 a	18.8 ± 2.0	12.1 ± 1.3 b
	55-437	1.04 ± 0.1 a	1.86 ± 0.2 a	12 ± 0.3 a	19.4 ± 2.0	13.4 ± 2.0 b
	Pr > F	**0.00**	**0.00**	**0.00**	NS	**0.03**
Fertilization (F)	F0	0.78 ± 0.1	1.46 ± 0.1	-	19.2 ± 1.8	13.1 ± 1.2
	F1	1.02 ± 0.1	2.03 ± 0.1	-	21.0 ± 2.0	15.4 ± 1.8
	Pr > F	**0.00**	**0.00**	-	NS	NS
BF x Var	BF1 x Fleur 11		1.93 ± 0.2 b	8 ± 0.2 b		
	BF1 x 55-33		2.09 ± 0.2 a	12 ± 0.1 a		
	BF1 x 55-437		2.53 ± 0.3 a	12 ± 0.3 a		
	BF2 x Fleur11		1.37 ± 0.1 c	5 ± 0.3 c		
	BF2 x 55-33		1.37 ± 0.1 c	11 ± 0.4 b		
	BF2 x 55-437		1.19 ± 0.2 c	11 ± 0.6 b		
	Pr > F	NS	**0.05**	**0.04**	NS	NS
F x Var	F0 x Fleur 11	0.66 ± 0.1	1.47 ± 0.1 b	-	18.25 ± 3.0 b	13.82 ± 2.4
	F0 x 55-33	0.84 ± 0.1	1.47 ± 0.1 b	-	18.12 ± 3.0 b	11.41 ± 1.7
	F0 x 55-437	0.85 ± 0.2	1.45 ± 0.3 b	-	21.19 ± 3.6 ab	14.20 ± 2.1
	F1 x Fleur 11	0.65 ± 0.2	1.83 ± 0.2 b	-	25.80 ± 4.7 a	20.97 ± 3.4
	F1 x 55-33	1.18 ± 0.2	2.00 ± 0.2 a	-	19.58 ± 2.9 ab	12.79 ± 2.2
	F1 x 55-437	1.23 ± 0.2	2.27 ± 0.3 a	-	17.69 ± 1.7 ab	12.52 ± 3.3
	Pr > F	**0.05**	**0.05**	-	**0.05**	0.08
BF x F	***Pr > F***	NS	**NS**	-	NS	0.07

3.3. Symbiotic interactions with soil organisms are influenced by both variety and fertilization practices.

The number of nodules on groundnut roots averaged 114 per plant 60 days after sowing (full flowering). Variety had no significant effect on nodule number or dry weight in any field type. Mineral fertilizer increased nodulation in all varieties except Fleur 11, while rhizobial inoculation had no significant effect (Table 5). Nodules correlated positively with haulm biomass ($r^2= 0.40$; $p< 0.000$) and pods per plant ($r^2= 0.42$; $p< 0.0000$) at flowering. Fleur 11 exhibited lower mycorrhization intensity than varieties 55-33 and 55-437, though it was only significant in BF1. Mineral fertilizer reduced the frequency and intensity of mycorrhization in BF1 (Table 5).

Table 4: Stepwise linear regression of seed and haulm yields as a function of the variables indicated in the first column. B= non-standardized coefficient± standard error; Beta = centered-reduced regression coefficients; P < 0.05 indicates that the predictor is a significant addition to the model.

	Seed yields (t ha^{-1})			Haulm (t ha^{-1})		
	Coefficient (B)	P	Beta coefficient (ß)	Coefficient (B)	P	Beta coefficient (ß)
Intercept	0.15± 0.26	0.58		0.89 ± 0.16	0.00	
1- Number of dead seedlings (%)	-0.01 ± 0.00	0.00	-0.29 ± 0.1			
2- Pods attacked by fungi (%)	-0.02 ± 0.01	0.04	-0.21 ± 0.1			
3- pH water						
4- C %	2.54 ±0.51	0.00	0.51 ± 0.1			
5- Bulk density over 0-30 cm (g cm^{-3})						
6- Number of nodules plant^{-1}				0.01 ± 0.00	0.00	0.61 ± 0.10
7- Mycorrhization intensity (%)						
R²	0.57			0.38		

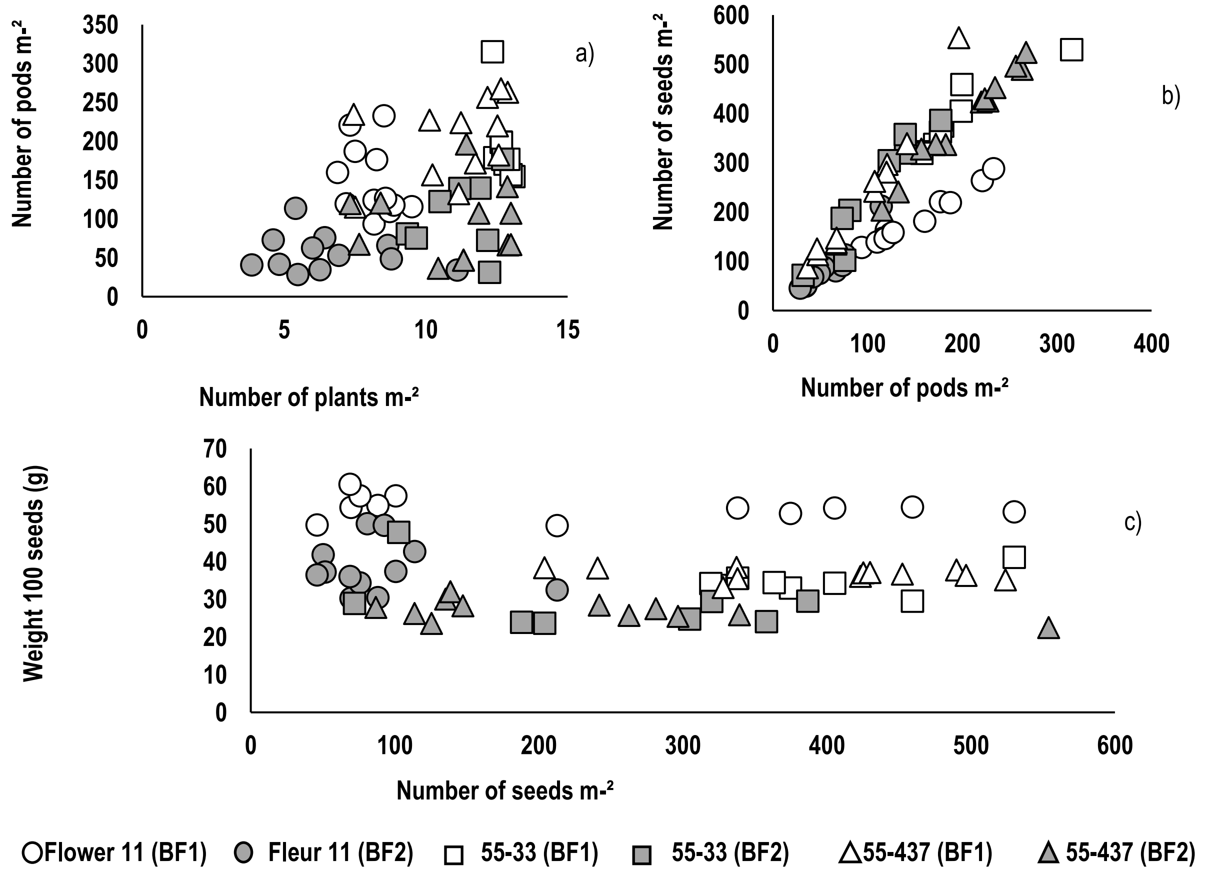

Figure 3: Relationships between successive components of groundnut seed yield. BF1: bush field 1; BF2: bush field 2

3.4. Non-significant effects of rhizobial inoculation

Rhizobial inoculation did not result in significant yield differences across any groundnut variety. Additionally, it had no notable impact on the seedling mortality rate, the incidence of immature pods or pods affected by bio-aggressors, nor on groundnut nodulation and mycorrhization (data not shown).

Table 5: Number and weight of nodules, frequency and intensity of mycorrhization of groundnut roots at 60 days after sowing according to treatments. BF1: bush field 1; BF2: bush field 2; NS: not significant (p> 0.05). Non-significant interactions are not detailed.

Factors		**Number of nodules plant^{-1}**	**Dry weight plant nodules^{-1} (g)**	**Mycorrhization frequency (%)**	**Mycorrhization intensity (%)**
Field type (BF)	BF1	177.24 ± 11.8 a	0.35 ± 0.0 a	83.10 ± 2.2 b	35.75 ± 3.4 b
	BF2	85.87 ± 4.1 b	0.16 ± 0.0 b	94.65 ± 1.8 a	44.53 ± 2.3 a
	Pr > F	**0.00**	**0.00**	**0.00**	**0.04**
Variety (Var)	Flower 11	104.18 ± 11.3	0.22 ± 0.0	87.77 ± 2.6	29.02 ± 3.1 b
	55-33	122.17 ± 8.9	0.23 ± 0.0	87.58 ± 3.0	43.43 ± 3.9 a
	55-437	118.59 ± 9.4	0.22 ± 0.0	90.63 ± 2.2	48.99 ± 3.4 a
	Pr > F	NS	NS	NS	**0.00**
Fertilization (F)	F0	96.94 ± 7.2 b	0.19 ± 0.0 b	90.04 ± 2.3	43.13 ± 3.1
	F1	131.24 ± 8.3 a	0.25 ± 0.0 a	87.51 ± 2.0	37.40 ± 2.9
	Pr > F	**0.00**	**0.00**	NS	NS
BF x Var	BF1 x Fleur 11			76.08 ± 3.8 b	17.94 ± 4.5 b
	BF1 x 55-33			83.76 ± 3.9 b	40.80 ± 6.6 a
	BF1 x 55-437			89.86 ± 2.9 ab	50.02 ± 4.6 a
	BF2 x Fleur 11			100.00 a	40.61 ± 2.7 a
	BF2 x 55-33			91.39 ± 4.4 a	46.06 ± 4.4 a
	BF2 x 55-437			91.56 ± 3.4 a	47.70 ± 5.2 a
	Pr > F	NS	NS	**0.00**	**0.02**
F x Var	***Pr > F***	NS	NS	NS	NS
BF x F	BF1 x F0			88.48 ± 2.9 a	45.29 ± 4.2 a
	BF2 x F0			92.0 ± 3.7 a	40.36 ± 4.4 a
	BF1 x F1			78.4 ± 2.9 b	26.80 ± 4.9 b
	BF2 x F1			96.4 ± 1.6 a	47.39 ± 2.5 a
	Pr > F	NS	NS	**0.00**	**0.00**

4. Discussion:

Regardless of the fertility level of the field (BF1, BF2), the ranking of the varieties remains consistent for both seed and haulm yields: Fleur 11<55-33 and 55-437. The seed yields of groundnut varieties 55-33 and 55-437 are at 50% of their potential, whereas those of Fleur 11 are around 25% of their potential. This discrepancy is mainly due to Fleur 11's higher vulnerability to fungal diseases, particularly seedling blight and pod rot. These findings align with Cl*avel et al (1997),* who note Fleur 11's susceptibility to *Aspergillus niger*, and Subrahmanyam et al (1992), who highlight the significant impact of these fungal diseases on groundnut yields in Sahelian regions, especially under severe water stress conditions.

In soil richer in carbon and nutrients, where rainwater infiltration capacity (as indicated by soil bulk density) was more favorable (BF1), damage from these diseases was reduced. This implies that the organic matter content and overall chemical and physical fertility of the soil play a role in controlling disease infestations. These findings are consistent with Kankam et al. (2022), who indicated that organic matter enhances crop nutrition and disease resistance, stimulates biological activity in soils, and contributes to natural bio-aggressor control. Additionally, Subrahmanyam et al. (1992) suggested that water deficit promotes the development of these diseases. Chemical fertilization did not mitigate disease symptoms, but it contributed to mineral nutrition and increased the yield of varieties less affected by these diseases. This result corroborates the stepwise regression analysis, which highlights soil fertility and diseases as two major limiting factors for groundnut yield.

The available references indicate that, in addition to organic amendments, other technical options could contribute to the control of these diseases. Notably, reducing the sources of primary infestation by avoiding the use of seeds already contaminated with fungal spores should not be overlooked (Subrahmanyam et al., 1992). This risk was mitigated in our trials by using healthy seeds, but it remains significant in most farmers' plots in the region, as they typically use untreated seeds from previous harvests. While fungicide seed treatment, an option already proposed by research, could be a viable alternative to reduce the risk of disease under these conditions, it should also be evaluated for its potential adverse effects on ecological services related to symbiotic nitrogen fixation and mycorrhization of groundnut (Rathjen et al., 2020; Dos Santos et al., 2021). Another strategy for mitigating disease risk in these agroecosystems could be lengthening and diversifying crop rotations to decrease soil inoculum levels before planting groundnuts (Subrahmanyam et al., 1992). Lastly, our findings affirm that selecting appropriate groundnut varieties is an effective measure for controlling bio-aggressor attacks.

The three varieties studied demonstrated robust nodulation capacity, indicating efficient nitrogen fixation. Our nodulation values are comparable to those observed by Bekele et al. (2023) in Ethiopia, Didagbé et al. (2014) in Benin, and Amba et al. (2013) in Nigeria on groundnut without fertilizer application. Fertilizer application enhanced nodulation, suggesting that nutrient availability, particularly phosphorus, is a limiting factor for symbiotic nitrogen fixation in the soils studied, consistent with the conclusions of Bado et al. (2006) on these agroecosystems.

Our mycorrhization values align with those documented by Bouhraoua et al. (2015) and Elsayed et al. (2000) on groundnut and are notably higher than those reported by Pérez et al. (2017) on phosphorus-rich soil-grown groundnut. The increase in mycorrhization on the least fertile soil in our system (BF2) corresponds with the findings of Ndeko et al. (2023), which indicate a decrease in mycorrhization when phosphate fertilization increases at an experimental station. Mycorrhization intensity doubled on the most degraded soil but they did not allow achieve groundnut yields comparable to the more fertile soil (BF1).

Fertilization significantly increased yields, especially in the more fertile soil (BF1). However, due to probable disease impact, Fleur 11 showed the least response to fertilization in terms of both yield and nodulation, and with a mycorrhization rate 30% lower than other varieties. Our findings on inoculation effects suggest that adding inoculum may not be necessary. This interpretation agrees with the observation that local strains were sufficiently effective to produce a high average number of nodules, which correlated well with the crop's vegetative biomass. Further detailed studies on bacterial inoculation of groundnuts and its variability in sub-Saharan agrosystems are recommended prior to regional implementation of this technical option.

5. Conclusion

Our findings indicate that fungal diseases are a significant barrier to enhancing groundnut yields. These diseases may also potentially affect the crop's symbiotic interactions with soil organisms in the studied agrosystems. However, both diseases and symbiosis with soil microbes are often overlooked in current cropping models. To achieve optimal crop health, resilience to climate change and yield improvement, an integrated strategy should be implemented. This strategy would encompass the selection of resistant varieties that exhibit strong symbiotic potential with soil microorganisms, the addition of both organic and mineral amendments, the use of disease-free seeds, and the adoption of diverse crop rotations. In this regard, varieties 55-33 and 55-437 are particularly well-suited.

Ethics

The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors have used artificial intelligence-assisted technologies to translate from French to English.

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Declaration of interest

The authors declare that they do not work for, advise, own shares in or receive funds from any organization that could benefit from this article, and declare no affiliation other than those mentioned at the beginning of the article.

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