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Growth promotion and yield attribute improvement of five groundnut (*Arachis hypogaea* L.) varieties by the application of plant growth promoting rhizobacteria

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The aim of this investigation was to evaluate the symbiotic performance of a collection of ten plant growth-promoting rhizobacteria (PGPR) strains on the growth and yield attributes of five groundnut varieties. The screening was conducted in the greenhouse using seeds of the varieties Essamay, Amoul Morom, 55-437, Fleur 11 and Sunu Gaal grown in 1.5 kg pots with Sangalkam soils. Leaf chlorophyll content, plant height, number of branches, biomass production, number and mass of pods were the parameters evaluated in response to groundnut inoculation. Overall, the results highlighted the effectiveness of inoculation with certain PGPRs on the growth and yield parameters. However, the effects of the inoculants were highly dependent on the variety used and the parameter studied. In particular, the strains RF8, SI12, SR6, SI16, SI27 and SS10 were the most efficient in improving the plant growth and yield attributes of the varieties Essamay, Amoul Morom and Sunu Gaal. In contrast, Fleur 11 and 55-437 were less responsive in terms of yield attributes, demonstrating that the response to groundnut inoculation is variety dependent. In addition, a significant increase in the estimated leaf chlorophyll content was only observed in Fleur 11 and Sunu Gaal, which was not expected and could be attributed to a lower N_2 fixation capacity of the indigenous rhizobia. Nevertheless, the increases in growth and yield parameters obtained in this study can be considered as a promising data for the use of bacterial biofertilisers in groundnut cultivation.

Key words: Peanut cultivars, biofertilizer, plant growth-promoting rhizobacteria (PGPR), inoculation, growth and yield parameters.

INTRODUCTION

The groundnut, also known as peanut (*Arachis hypogaea* L.), is an important grain legume native to Latin America (Sene et al., 2010; Noba et al., 2014; Sene et al., 2023a). More than 300 varieties are cultivated in the tropics and subtropics, including sub-Saharan Africa (Sene et al., 2010; Noba et al., 2014; Jayaprakash et al., 2019; Sene et al., 2023a), making groundnut the most important food legume crop (Alexander et al., 2020). It is the main livelihood of many smallholder farmers in tropical and subtropical regions of the world (Mekdad et al., 2021).

The nutritional and economic importance of groundnut lies in the fact that it is an oil-protein crop with multiple food and feed uses (seed, oil, cake, tops, shells etc.) (Alexander et al., 2020).

Groundnut has been a cash crop in Senegal for more than a century, and contributes to 60% of the countries' agricultural gross domestic product (GDP). This legume accounts for about 80% of Senegal's export earnings (Sene et al., 2010, 2023a). After a long period of decline, groundnut yields have increased over the past five years. However, the factors determining this increase, that is soil fertility have gradually deteriorated, with a reduction in fallow land and low fertiliser use (Sene et al., 2021, 2023a, 2023b). Various agricultural practices, including the use of mineral fertilizers, have been adopted to increase yields and alleviate food shortages (Noba et al., 2014; Sene et al., 2023c). However, the high cost of chemical fertilizers and the need for sustainable alternative sources has increased the strategic importance of harnessing soil microorganisms. Together with rhizobia and mycorrhizal fungi, PGPBs provide an alternative to mineral fertilizers and a means to maintain or improve soil fertility (Kotasthane et al., 2017; Nath et al., 2017; Lau et al., 2020; Lotfi et al., 2022; Kandasamy and Kathirvel, 2023; Sene et al., 2023b).

Several studies have shown that the soil biofertilisation techniques can increase crop production while protecting the environment for environmental sustainability (Alabouvette and Cordier, 2018; Nagrale et al., 2023; Sene et al., 2023b). Both mycorrhizal fungi and symbiotic bacteria are currently attracting much scientific interest due to their potential to improve nutrient use efficiency (NUE), facilitate nutrient uptake, promote growth (Frank et al., 2017; Hamim et al., 2019; Nagrale et al., 2023) and protect the host from predators through the production of secondary metabolites (Kandasamy and Kathirvel, 2023). Several PGPBs, rhizobia or arbuscular mycorrhizal fungi have been commercialized either as biocontrol agents or biofertilizers (Vessey, 2003; Lesueur et al., 2016; Mohanty and Swain, 2018; Nagrale et al., 2023). However, the commercialization of microbial inoculants in West Africa has lagged behind the expectations (Sene et al., 2023a, b). PGPRs are important contributors to soil fertility improvement, bioremediation and stress management for the development of environmentally sustainable agriculture (Prasad et al., 2019; Lau et al., 2020; Kandasamy and Kathirvel, 2023; Nagrale et al., 2023).

These are rhizosphere bacteria that are directly or indirectly involved in promoting plant growth and development (Lau et al., 2020; Kandasamy and Kathirvel, 2023). They release phytohormones, modify endogenous levels of these phytohormones, improve nutrient availability and uptake, and reduce the harmful effects of pathogenic microorganisms on plants (Prasad et al., 2019; Lau et al., 2020; Steiner et al., 2021; Kandasamy and Kathirvel, 2023). It is possible to improve the functioning of PGPRs by providing crop plants with a significant amount of these selected microorganisms (Lau et al., 2020; Nagrale et al., 2023). This technique is known as inoculation. The problem of groundnut inoculation in West African areas is mainly related to the lack of compatibility with the crop varieties or competitiveness of the inoculated strains (Sene et al., 2010, 2023b). The present study was conducted based on the following two hypotheses: (i) Inoculation with an effective PGPR strain could help groundnut plants to ensure a better productivity (Alexander et al., 2019, 2020); (ii) Groundnut inoculation may well be effective, but depends on the variety and the inoculant used (Sene et al., 2010). Furthermore, some authors have reported that modern high-yielding and traditional varieties differ in their response to microbial inoculation (Chen et al., 2003; Meghvansi et al., 2008; Argaw, 2017). This suggests the need for variety-specific inoculant selection prior to inoculum formulation. Therefore, the study aimed to evaluate the symbiotic performance of ten PGPR strains on five modern and traditional Senegalese groundnut varieties.

MATERIALS AND METHODS

Plant

Five local groundnut (*A. hypogaea* L.) varieties kindly provided by the Centre National de Recherche Agronomique (CNRA) in Bambey, Senegal, were used in this experiment. These varieties were selected on the basis of the taste desired by the local population and their characteristics as shown in Table 1.

PGPR materials

The PGPR strains used in this study were from the collection of the Laboratoire Commun de Microbiologie (LCM) IRD/ISRA/UCAD, Dakar, Senegal. The ten strains were isolated from roots and rhizosphere soils of *Dichrostachys cinerea* (L.) Wight & Arn. by Bambara (2019). These isolates were characterized and screened for the following PGP activities: Phosphate (P) solubilization, auxin, amminia and sederophore production, and fluorescence emission under ultraviolet irradiation. The *in vitro* screening provided sufficient evidence for further *in vivo* plant growth-promotion testing of the ten isolates.

Greenhouse experimental design

The experiment was set up in the greenhouse (Bel Air Experimental

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Table 1. Characteristics of the groundnut varieties used in the study.

Variety	Type	Growth habit	Growth cycle (days)	Registration in Senegal
Fleur 11	Spanish	Erect	90	Traditional, since 1955
55-437	Spanish	Erect	90	Traditional, since 1993
Sunu Gaal	Spanish	Erect	95	New, since 2017
Essamay	Virginia	Semi-erect	105	New, since 2017
Amoul Morom	Virginia	Semi-erect	120	New, since 2017

Station, 14°44'N, 17°30'W in Dakar) using a non-sterile soil from Sangalkam, 30 km east of Dakar mixed with sterilized vermiculite at 120°C for 20 min (1:1, v/v). This soil has a pH of 6.5 with 58.15, 32.8 and 3.6% of sand, loam and clay, respectively and contains 0.06% total nitrogen (N), 0.54% total carbon (C), 39 mg phosphorus (P) kg^{-1} total P and 4.8 mg P kg^{-1} available P. It was sieved (< 1 mm), homogenized and used to fill up the pots. Seeds of selected varieties (listed in Table 1) of groundnut were first surface sterilized (to avoid seed-borne diseases) with 5% sodium hypochlorite (NaOCl) for 5 min, 70% ethanol for 3 min and thoroughly rinsed with sterile distilled water. The seeds were then placed on Petri dishes containing moist filter paper for germination under sterile conditions and kept in the dark at 25°C. The germinated seeds were manually transplanted into 1.5 L plastic pots disinfected with a solution containing 1.81% of calcium hypochlorite and filled with the substrate to a depth of 2 to 3 cm. Two germinated seeds were planted in each pot. The plants were thinned on the 3rd day after planting at one plant per pot. The pots were arranged in randomized blocks, with a single inoculation and five replications. The pots were placed at 10 and 40 cm spacing within and between rows for the varieties Fleur 11, 55-437 and Sunu Gaal. The distance between the pots was 10 and 60 cm for the varieties Amoul Morom and Essamay. The plants were grown for 65 days under greenhouse conditions (temperature of 27 to 35°C, relative humidity of 70 to 80% and 12 h of light) and were watered every two days with chlorinated tap water without added nutrients.

Inoculant preparation and inoculation

The greenhouse experiment consisted of 11 treatments: Ten with application of indigenous PGPR inoculants compared to a negative control without inoculation for each variety. The inoculants were prepared as follows. Each PGPR strain was grown in 250 mL Erlenmeyer flasks containing 100 mL of yeast extract-mannitol (YEM) medium (Vincent, 1970) for 3 days at 28°C with rotary shaking at 150 rpm. Five milliliters (containing 10^8 cells mL^{-1}) of the bacterial culture at its logarithmic growth stage were used to inoculate the plants. The inoculants were applied directly to the soil surface at the base of the stem five days after emergence to ensure that the bacteria reached the roots. Treatments without bradyrhizobial inoculum received 5 mL of autoclaved inoculum in order to avoid differences in soil nutrient content associated with the addition of rhizobial inoculum.

Collection of growth and yield variables

Data on growth variables (plant height and number of branches) and leaf chlorophyll content for each variety were collected at pod maturity periods (60 DAP). Plant height (cm) was measured with a ruler from the base of the stem to the apex, while the number of branches was counted manually. Leaf chlorophyll content was estimated at 65 DAP using a SPAD-502Plus chlorophyll meter (Konica-Minolta). At harvest, whole groundnut plants were uprooted. The soil adhering to the roots was removed under running tap water. The pods were manually stripped from the plants to record the yield components. For each variety, above-ground biomass and the yield attributes (number of pods per plant, pod weight) were determined. Above-ground biomass and the yield attributes were determined by weighing sample parts after over-drying to constant weight at 65°C.

Data analyses

All data were tested for normality and homogeneity using the Shapiro-Wilk and Levene tests, respectively. Data for plant growth and yield parameters were statistically analyzed using univariate analysis with one-way analysis of variance (ANOVA) using the R software v3.4.4 (R Core Team, 2020). Significantly different means and standard deviations were separated using the Tukey (HSD) test at the 5% probability threshold.

RESULTS

Growth response of groundnut varieties to PGPR inoculation

One-way analysis of variance (ANOVA) followed by Tukey's means comparison test (HSD) at the 5% threshold showed that plant height varied significantly between treatments for all varieties (Table 2). For the Amoul Morom variety, only the RF8 and SI12 isolates significantly improved plant height with 23.6 ± 1.92 and 24 ± 1.37 cm respectively compared to the control, which had a mean height of 19.8 ± 0.52 cm. In the Essamay variety, it was the strains SI27 (23.6 ± 2.06 cm) and SR6 (26.3 ± 1.65 cm) that significantly increased plant height compared to the control (18.7 ± 0.95 cm). Strains RI16 and SR6 were the only ones to increase the height of plants of variety 55-437 with 28.3 ± 1.09 and 22.2 ± 1.12 cm, respectively. Plants of variety Fleur 11 inoculated with the strains SI27 (22.4 ± 2.82 cm), SR16 (23.0 ± 2.37 cm), SS10 (23.2 ± 1.24 cm) and ST10 (24.1 ± 0.78 cm) showed the highest height compared to the control plants (18.1 ± 1.03 cm). In the Sunu Gaal variety, a significant improvement in plant height growth was only observed for variety SS10 (28.2 ± 0.93 cm).

Incidence of PGPR inoculation on plant collar diameter

The ANOVA showed a significant difference ($p<0.05$) in collar diameter between treatments and for all varieties

Table 2. Growth (plant height and collar diameter) response of groundnut varieties (*A. hypogaea*) to single inoculation with PGPR strains 65 days after planting.

Treatment	Groundnut variety									
	Amoul Morom		Essamaye		55-437		Fleur11		Sunu Gaal	
	Height (cm)	CD (mm)	Height (cm)	CD (mm)	Height (cm)	CD (mm)	Height (cm)	CD (mm)	Height (cm)	CD (mm)
ED9	21.3±1.26^{abc}	4.1±0.67^{ab}	22.5±2.97^{abc}	4.6±0.18^{ab}	21.4±0.54^{bc}	3.9 ± 0.57^{a}	20.2±1.87^{abc}	3.7±0.23^{ab}	25.2±1.51^{abcd}	5.0±0.18^{ab}
EF10	20.2±1.90^{c}	3.5±0.46^{b}	21.7±1.75^{abc}	4.4±0.78^{abc}	21.2±1.39^{bc}	4.4 ± 0.25^{a}	19.8±0.76^{abc}	3.5±0.37^{ab}	26.1±0.87^{abcd}	4.9±0.18^{ab}
RF8	23.6±1.92^{ab}	5.0±0.65^{a}	19.5±1.08^{bc}	4.9±0.97^{abc}	21.0±1.19^{bc}	3.7 ± 0.17^{a}	19.8±1.56^{abc}	3.4±0.15^{b}	22.9±1.23^{d}	5.0±0.42^{ab}
RI16	20.4±0.79^{c}	4.8±0.79^{ab}	19.2±0.94^{bc}	3.9±0.80^{bc}	28.3±1.09^{a}	4.5 ± 0.20^{a}	18.9±1.18^{bc}	3.9±0.59^{ab}	24.0±0.99^{cd}	4.6±0.11^{ab}
SI12	24.0±1.37^{a}	5.2±0.74^{a}	23.6±2.06^{ab}	5.1±1.16^{ab}	21.2±1.24^{bc}	3.5 ± 0.29^{a}	21.4±0.77^{abc}	3.4±0.28^{b}	25.6±1.03^{abcd}	4.6±0.25^{ab}
SI27	20.0±0.33^{c}	4.6±0.34^{ab}	21.9±2.64^{abc}	3.3±0.54^{c}	21.7±1.60^{bc}	3.7 ± 0.64^{a}	22.4±2.82^{ab}	4.5±0.29^{a}	27.1±1.12^{ab}	5.2±0.61^{a}
SR16	22.0±0.54^{abc}	4.9±0.68^{ab}	19.6±2.41^{bc}	4.3±0.32^{abc}	20.1±1.31^{bc}	4.1 ± 0.44^{a}	23.0±2.37^{a}	4.2±0.43^{ab}	26.2±0.76^{abcd}	4.8±0.58^{ab}
SR6	20.7±1.59^{bc}	5.0±0.36^{a}	26.3±1.65^{a}	5.4±1.33^{a}	22.2±1.12^{b}	4.4 ± 0.38^{a}	19.6±0.84^{abc}	3.5±0.20^{b}	25.3±1.05^{abcd}	4.8±0.48^{ab}
SS10	22.7±0.54^{abc}	4.2±0.52^{ab}	19.6±1.63^{bc}	4.9±0.45^{ab}	20.3±0.49^{bc}	3.4 ± 0.97^{a}	23.2±1.24^{a}	4.1±0.43^{ab}	28.2±0.93^{a}	5.4±0.97^{a}
ST10	20.2±0.95^{c}	3.8±0.25^{ab}	19.4±2.56^{bc}	3.9±0.17^{bc}	20.5±0.61^{bc}	3.6 ± 0.49^{a}	24.1±0.78^{a}	3.6±0.54^{ab}	26.3±1.96^{abc}	5.1±0.24^{ab}
Control	19.8±0.52^{c}	3.9±0.82^{ab}	18.7±0.95^{c}	4.5±0.23^{ab}	18.2±1.39^{c}	3.4 ± 0.19^{a}	18.1±1.03^{c}	3.9±0.53^{ab}	24.1±1.65^{bcd}	4.0±0.35^{b}
Mean ± sd	21.3±1.79	4.5±0.78	21.1±2.88	4.5±0.88	21.6±2.53	3.9±0.58	20.8±2.26	3.8±0.48	25.5±1.81	4.8±0.54
CV (%)	5.618897	13.48099	9.466973	11.27467	5.367065	12.29748	7.507155	10.00039	4.913711	9.52718
P-value	2.69e^{-05}***	0.00156**	6.97e^{-05}***	0.00012***	4.34e^{-10}***	0.00973**	0.000204***	0.00455**	8.72e^{-05}***	0.0232*

CD, Collar diameter; Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 (significant differences according to Tukey test); ns, not significant difference; Mean ± sd (mean ± standard deviation); CV, Coefficient of variation. Values, mean ± standard deviation with the same superscript letter within a column are not statistically different at the 5% probability according to Tukey test.

(Table 2). An increase in collar diameter was only observed for the strains SI27 (5.2 ± 0.61 mm) and SS10 (5.4 ± 0.97 mm) inoculated on plants of the variety Sunu Gaal. However, no significant difference was observed among treatments for the varieties Amoul Morom, Essamay, 55-437 and Fleur 11.

Estimated leaf chlorophyll content

Estimated leaf chlorophyll content showed that only Fleur 11 and Sunu Gaal exhibited significant differences compared to the control plants (Table 3). Isolates SI27 (33.2 ± 0.98), SR16 (34.1 ± 1.79) and SS10 (34.2 ± 1.36) significantly increased leaf chlorophyll content in Fleur 11 compared to the control (28.8 ± 1.60). In Sunu Gaal, the strains SI27 (43.0 ± 1.44), SS10 (41.4 ± 0.86) and ST10 (41.5 ± 1.09) increased the leaf chlorophyll content compared to the control (36.8 ± 0.42).

Groundnut dry matter production

The results showed significant increases in plant dry matter when variety Amoul Morom was inoculated with RF8 (3.4 ± 0.38 g), SI12 (3.2 ± 0.33 g) and SS10 (3.3 ± 0.32 g) (Table 4). In Essamay, the three inoculated treatments EF10 (2.5 ± 0.80 g), SI12 (2.6 ± 0.37 g) and SR6 (3.5 ± 0.40 g) also increased plant biomass compared to the control (1.7 ± 0.21). Similarly, plants of variety 55-437 inoculated with RF8, RI16, SI27 and SR6 showed a better biomass production compared to the control. However, plants inoculated with SR16, SI27 and ST10 showed a decrease in biomass production. In variety Fleur 11, an increase in dry plant biomass was observed with RF8 (1.7 ± 0.10 g), SI27 (2.7 ± 0.28 g) and SS10 (2.2 ± 0.41 g). All strains inoculated on Sunu Gaal showed significant increases in plant biomass production.

Yield attributes in response to groundnut inoculation

For Amoul Morom and 55-437, 40% of the treatments improved yield attributes, and for Essamay and Fleur 11, 30% of the treatments

Table 3. Estimated leaf chlorophyll content at 65 days after planting in response to groundnut varieties (*A. hypogaea*) single inoculation with PGPR strains.

Treatment	Groundnut variety				
	Amoul Morom	**Essamay**	**55-437**	**Fleur 11**	**Sunu Gaal**
ED9	39.7±0.43^{abcd}	31.4±1.73^{b}	31.4±1.04^{ab}	28.8±1.60^{c}	37.1±1.03^{d}
EF10	38.7±0.67^{cd}	35.1±2.40^{ab}	31.5±3.01^{ab}	29.2±1.00^{bc}	38.1±1.44^{d}
RF8	41.2±1.42^{ab}	32.1±1.88^{b}	32.3±2.50^{ab}	30.2±1.85^{abc}	38.9±0.46^{cd}
RI16	38.9±0.64^{bcd}	33.5±1.87^{ab}	34.4±3.48^{a}	31.1±2.27^{abc}	38.3±1.32^{d}
SI12	42.1±1.50^{a}	37.8±2.95^{a}	31.6±3.91^{ab}	30.9±0.54^{abc}	39.0±0.90^{bcd}
SI27	38.4±1.53^{d}	30.7±1.91^{b}	28.2±0.71^{b}	33.2±0.98^{ab}	43.0±1.44^{a}
SR16	40.2±0.68^{abcd}	33.4±1.56^{ab}	28.5±1.74^{b}	34.1±1.79^{a}	39.3±1.22^{bcd}
SR6	39.9±0.57^{abcd}	35.1±2.52^{ab}	31.8±2.54^{ab}	31.0±2.81^{abc}	37.9±1.19^{d}
SS10	40.0±0.66^{abcd}	32.9±2.92^{ab}	28.3±1.15^{b}	34.2±1.36^{a}	41.4±0.86^{abc}
ST10	41.1±1.05^{abc}	30.3±1.56^{b}	28.4±1.29^{b}	32.5±0.07^{abc}	41.5±1.09^{ab}
Control	39.8±0.90^{abcd}	32.9±2.92^{ab}	31.4±1.04^{ab}	28.8±1.60^{c}	36.8±0.42^{d}
Mean ± sd	40.0±1.38	33.2±2.89	30.8±2.82	31.2±2.42	39.2±2.15
CV (%)	2.476021	6.822973	7.533173	5.410251	2.761981
P-value	0.000179***	0.00208**	0.00835**	0.000248***	8.06e^{-09}***

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 (significant differences according to Tukey test); ns, not significant difference; Mean ± sd (mean ± standard deviation); CV coefficient of variation. Values, mean ± standard deviation with the same superscript letter within a column are not statistically different at the 5% probability according to Tukey test.

improved yield characteristics. For Sunu Gaal, 80% of the inoculated treatments improved yield attributes. As the plants were harvested before maturity, it is expected that the yield at pod maturity of the inoculated plants will be significantly higher. In terms of pod yield attributes, the tested isolates increased the number of pods on the variety Amoul Morom, with the exception of SI27, SR16, SR6 and ST10. On variety Essamay, inoculation with ED9, SI12 and SR6 increased the number of pods with 6.5 ± 0.58, 7.0 ± 0.00 and 7.0 ± 0.82, respectively, compared to the control (3.5 ± 0.58). For variety 55-437, RF8 (4.8 ± 0.50), RI16 (5.7 ± 0.58), SR6 (5.3 ± 0.50) and ST10 (5.0 ± 0.00) showed the better increases in pod number. However, only plants inoculated with RI16, SI27 and SS10 showed a higher number of pods in Fleur 11 (Table 5).

The variety Amoul Morom showed significant increases in pod biomass, except for the strains RI16, SR16, SR6 and ST10. For Essamay, only RI16, SI27 and SR16 were not able to yield significant pod biomass. No significant difference was observed for Fleur 11 treatments and only RI16 and SR6 increased the pod biomass for variety 55-437. All tested isolates significantly improved the pod biomass of Sunu Gaal (Table 5).

DISCUSSION

Sustainable agriculture is a major challenge to ensure optimal yields while protecting the environment. Plant growth promoting bacteria (PGPB) are recognized as one of the most important bacteria capable of forming beneficial associations with plants to increase their productivity, protect them from diseases and abiotic stresses, and reduce the use of mineral fertilizers (Lau et al., 2020; Kandasamy and Kathirvel, 2023; Sene et al., 2021, 2023). These microorganisms are being promoted as biofertilizers to improve crop yields and minimise dependence on mineral fertilizers (Kandasamy and Kathirvel, 2023; Sene et al., 2021, 2023). The present work was conducted to evaluate the symbiotic performance of ten PGPR isolates from the collection of the Common Laboratory of Microbiology (LCM) IRD/ISRA/UCAD on five

Table 4. Biomass production (g) of groundnut varieties at harvest.

Treatment	Groundnut variety				
	Amoul Morom	**Essamay**	**55-437**	**Fleur 11**	**Sunu Gaal**
ED9	2.6±0.14^{bcd}	2.3±0.85^{cde}	1.0±0.37^{cde}	1.4±0.04^{bcd}	2.8±0.25^{abc}
EF10	3.0±0.58^{abcd}	2.5±0.80^{ab}	0.7±0.02^{de}	1.3±0.01^{bcd}	2.9±0.08^{abc}
RF8	3.4±0.38^{a}	2.4±0.24^{bcd}	1.3±0.01^{bc}	1.7±0.10^{b}	2.4±0.19^{c}
RI16	2.8±0.22^{abcd}	1.9±0.71^{de}	2.6±0.00^{a}	1.0±0.22^{d}	2.5±0.68^{c}
SI12	3.3±0.32^{ab}	2.6±0.37^{bc}	1.1±0.02^{cd}	1.4±0.10^{bcd}	2.8±0.21^{abc}
SI27	2.5±0.24^{bcd}	1.4±0.22^{e}	1.4±0.25^{bc}	2.7±0.28^{a}	3.6±0.37^{a}
SR16	2.6±0.47^{abcd}	1.5±0.20^{e}	0.6±0.17^{e}	1.5±0.13^{bcd}	2.6±0.07^{bc}
SR6	2.5±0.21^{bcd}	3.5±0.40^{a}	1.6±0.17^{b}	1.0±0.29^{cd}	2.9±0.66^{abc}
SS10	3.2±0.33^{abc}	2.4±0.24^{bcd}	0.6±0.26^{e}	2.2±0.41^{a}	3.5±0.22^{ab}
ST10	2.4±0.33^{cd}	1.3±0.46^{de}	0.5±0.01^{e}	1.3±0.38^{bcd}	3.5±0.17^{ab}
Control	2.3±0.22^{d}	1.7±0.21^{de}	1.1±0.01^{cd}	1.0±0.09^{cd}	1.4±0.12^{d}
Mean ± sd	2.8±0.47	2.1±0.74	1.2±0.60	1.5±0.58	2.8±0.68
CV (%)	12.08689	14.47769	14.98897	14.34221	12.2841
P-value	0.000196***	4.74e^{-10}***	3.27e^{-16}***	1.22e^{-11}***	1.39e^{-08}***

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 (significant differences according to Tukey test); ns, not significant difference; Mean ± sd (mean ± standard deviation); CV coefficient of variation. Values, mean ± standard deviation with the same superscript letter within a column are not statistically different at the 5% probability according to Tukey test.

Senegalese groundnut varieties. The results obtained in this study showed the effectiveness of groundnut inoculation with certain PGPR strains on plant growth and yield parameters. However, the results indicated that the response of groundnut to PGPR inoculation was highly dependent on the variety used.

Plant growth promoting rhizobacteria can not only promote plant growth, increase crop yield and control plant diseases and insect pests, but also have specific micro-ecological functions (Prasad et al., 2019; Lau et al., 2020; Kandasamy and Kathirvel, 2023; Nagrale et al., 2023). This study confirmed the ability of PGPR isolates to improve the growth and yield attributes of groundnut plants. Of the ten strains tested, eight showed improvements in either on the plant growth or yield characteristics. However, the results showed that the expression of the PGPRs to improve crop productivity depended on the variety considered. Indeed, the strains RF8, SI12, SR6, SI16, SI27 and SS10 strains significantly improved plant growth, especially when inoculated on the modern varieties Essamay, Amoul Morom and Sunu Gaal. In contrast, Fleur 11 and 55-437 were less responsive in terms of the yield attributes, demonstrating that groundnut inoculation is variety dependent. Discrepancies in the response of groundnut varieties toward microbial inoculation have been reported previously (Argaw, 2017; Sene et al., 2023a, c) and corroborate our findings. The results of this study are in agreement with those of Bassair and Lakhdar (2022), who showed that PGPR strains isolated and tested on watercress (*Lepidium sativum*) plants had the ability to stimulate the plant growth and biomass production. The results are also consistent with those reported by Adoko et al. (2021). These authors evaluated the efficacy of five strains of rhizobacteria on the growth of maize (*Zea mays* L.) plants under greenhouse conditions. Their results showed significant improvements in plant growth, stem diameter and leaf area. The ability of PGPRs to increase plant growth has been reported in several previous studies: Potato (*Solanum tuberosum* L.) (Ekin, 2019), moringa (*Moringa oleifera* Lam.) (Bencheikh et al., 2019), tomato (*Solanum lycopersicum* L.) (Kalozoumis et al., 2021), rice (*Oryza sativa* L.) (El-Mageed et al., 2022) or wheat (*Triticum aestivum* L.) (Larbi and Zourdani, 2022). In Senegal, groundnut has not been so far successfully inoculated with PGPR strains. Therefore, the increases in groundnut plant growth for some varieties should be considered as new promising data for further adoption of microbial inoculation technology for groundnut improvement in sub-Saharan Africa.

Chlorophyll pigment is an indicator of the degree of nitrogen assimilation by the plant and is responsible for the green colour of the leaves (Joly, 2018). In this study, a significant increase in the estimated leaf chlorophyll content was only observed in the varieties Fleur 11 (inoculated with strains SI27, SR16 and SS10) and Sunu Gaal (inoculated with strain EF10). Thus, more than half of the inoculated strains showed no ability to significantly increase the leaf chlorophyll content. These results were not expected and do not agree with those of Sania et al. (2023), who showed that the use of PGPRs as an inoculant of barley (*Hordeum vulgare* L.) seeds in saline soils improved the leaf chlorophyll content. As groundnut is a legume species, its biological nitrogen fixation is

Table 5. Yield attributes (number of pods per plant, pod weight) of groundnut varieties at harvest.

Treatment	Groundnut varieties									
	Amoul Morom		Essamaye		55-437		Fleur11		Sunu Gaal	
	Pod number	Weight of pods (g)	Pod number	Weight of pods (g)	Pod number	Weight of pods (g)	Pod number	Weight of pods (g)	Pod number	Weight of pods (g)
ED9	4.8±0.96^{bc}	0.8±0.02^{bcde}	6.5±0.58^{ab}	1.6±0.01^{ab}	3.8±0.96^{bc}	0.7±0.38^{cd}	5.5±0.58^{c}	1.4±0.15^{abc}	4.5±0.58^{de}	1.5±0.21^{a}
EF10	4.3±0.50^{bc}	0.9±0.06^{bc}	3.8±0.96^{c}	1.1±0.30^{bcd}	4.0±0.01^{bc}	0.4±0.01^{d}	6.0±1.00^{bc}	1.4±0.24^{abc}	4.5±0.58^{de}	1.4±0.35^{a}
RF8	6.5±0.58^{a}	1.3±0.09^{a}	4.8±0.50^{bc}	1.4±0.12^{bc}	4.8±0.50^{ab}	1.2±0.25^{bc}	5.8±0.96^{bc}	1.0±0.33^{bcd}	5.0±0.01^{cd}	1.5±0.20^{a}
RI16	4.5±0.58^{bc}	0.6±0.01^{ef}	4.5±1.29^{c}	0.6±0.17^{de}	5.7±0.58^{a}	1.6±0.40^{ab}	8.5±0.58^{a}	0.7±0.23^{d}	5.5±0.58^{cd}	1.4±0.11^{a}
SI12	5.3±0.50^{ab}	1.0±0.02^{b}	7.0±0.00^{a}	2.1±0.61^{a}	4.5±0.58^{abc}	0.7±0.05^{cd}	4.0±0.00^{c}	1.3±0.14^{abc}	5.5±0.58^{cd}	2.0±0.28^{a}
SI27	3.8±0.50^{cd}	0.9±0.07^{bc}	3.5±0.58^{c}	0.8±0.32^{cde}	4.0±1.15^{bc}	1.0±0.01^{bcd}	8.5±0.58^{a}	1.5±0.17^{ab}	7.5±1.73^{ab}	1.7±0.54^{a}
SR16	3.5±0.58^{cd}	0.7±0.03^{b-f}	4.8±0.96^{bc}	0.8±0.02^{de}	3.8±0.50^{bc}	0.6±0.23^{d}	6.0±0.01^{bc}	1.5±0.16^{ab}	5.7±0.58^{bcd}	1.5±0.05^{a}
SR6	3.5±0.58^{cd}	0.7±0.32^{cdef}	7.0±0.82^{a}	1.6±0.26^{ab}	5.3±0.50^{ab}	2.0±0.27^{a}	4.8±0.96^{c}	0.8±0.13^{cd}	6.8±0.96^{abc}	1.4±0.22^{a}
SS10	5.3±0.50^{ab}	0.9±0.11^{bcd}	4.5±0.58^{c}	1.6±0.23^{ab}	4.0±0.82^{bc}	0.6±0.41^{cd}	7.3±0.96^{ab}	1.7±0.40^{a}	8.5±0.58^{a}	1.7±0.28^{a}
ST10	3.8±0.50^{cd}	0.6±0.08^{def}	5.3±0.50^{abc}	0.9±0.05^{cd}	5.0±0.01^{ab}	0.6±0.02^{cd}	6.0±0.01^{bc}	0.9±0.08^{bcd}	6.5±0.58^{bc}	1.6±0.29^{a}
Control	2.5±0.58^{d}	0.5±0.08^{f}	3.5±0.58^{c}	0.3±0.03^{e}	3.0±0.01^{c}	0.5±0.26^{d}	4.3±0.50^{c}	1.5±0.34^{ab}	2.8±0.96^{e}	0.6±0.23^{b}
Mean ± sd	4.3±1.18	0.8±0.24	5.0±1.41	1.2±0.58	4.3±0.91	0.9±0.5	5.9±1.98	1.3±0.39	5.7±1.70	1.4±0.41
CV (%)	13.67071	14.61403	14.77098	22.52645	14.62355	29.11278	11.87707	19.72108	14.27426	18.34811
pValue	3.98e^{-09}***	1.08e^{-09}***	1.39e^{-08}***	1.26e^{-10}***	7.76e^{-05}***	1.57e^{-09}***	2.09e^{-12}***	2.11e^{-05}***	1.8e^{-09}***	1.57e^{-05}***

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 (significant differences according to Tukey test); ns (not significant difference); Mea ± sd (mean ± standard deviation); CV (coefficient of variation). Values (mean ± standard deviation) with the same superscript letter within a column are not statistically different at the 5% probability according to Tukey test.

mainly carried out in symbiotic association (Alexander et al., 2019), mainly with rhizobia. A low N_2-fixing capacity of the indigenous bacteria that formed the nodules with the plants could partly explain this result. The efficiency of N_2 fixation in groundnut was previously reported to result in the accumulation of nitrogen in plants which in turn reflects the synthesis of chlorophyll (Nageswara et al., 2001). Indeed, groundnut was considered to be a highly "promiscuous" species (Bogino et al., 2006), being nodulated by a wide variety of rhizobia. Thus, the efficacy of indigenous versus introduced bacteria on groundnut has always been questionable worldwide: India (Gaur et al., 1974; Nambiar, 1985; Joshi et al., 2008), Israel (Schiffmann and Alper, 1968), Brazil (Cardoso et al., 2009), Argentina (Castro et al., 1999; Bogino et al., 2006, 2008), Senegal (Sene et al., 2010) or Cameroon (Chotangui et al., 2022).

As expected, the results showed that plant dry matter and yield attributes were improved by 7 of the 10 PGPR strains tested (SS10, EF10, SR6, RF8, RI16, ED9 and SI27), with specificity depending on the variety used. These results are consistent with those of Pan et al. (2019), who reported a beneficial effect of PGPR on pod yield parameters and plant biomass production. Numerous other studies have also shown that the use of PGPR leads to improved crop yields. Results reported by Rubin et al. (2017) showed that inoculation of PGPR in a number of crop species resulted in higher pod production (28%) and biomass production (35%). The results are also supported by those of Demeule (2020), who showed a significant increase in dry matter by inoculation of PGPR in tomato (*Solanum lycopersicum* L.) and cucumber (*Cucumus sativus* L.) plants under greenhouse conditions. In Quebec (Canada), field trials showed that inoculation with *Pseudomonas* sp. PGPRs increased the yields of maize (*Zea mays* L.) and

lettuce (*Lactuca sativa* L.) (Sekhara Fawzi, 2022).

The results of this study also showed that plants of varieties Fleur and 55-437 inoculated with strains ST10, RF8, RI16, SR6 (for the former variety) and EF10 (for the latter variety) showed a reduction in the yield attributes biomass production, whereas they revealed positive effects on the other varieties compared to the controls. The same trend was observed for biomass production when Essamay and 55-437 were inoculated with SI27, SR16 and ST10 (for the former) and EF10, SR16 and ST10 (for the latter). This result contradicts the basic hypothesis and suggests that although these inoculated strains have confirmed PGPR properties under *in vitro* conditions, they are not necessarily effective in increasing plant biomass production for all varieties. Although PGPR can have a positive effect and promote plant growth through the production of growth hormones and pathogen suppression, it can also have a negative effect on plant growth. Indeed, when excess growth hormones are produced, plant growth is suppressed and the PGPRs are considered to be deleterious rhizobacteria (DRB) and therefore yield reducing bacteria (Phukan et al., 2021). These types of bacteria also negatively affect plant growth and yield through the production of phytotoxic substances (Kennedy, 2019). The results therefore highlighted the complexity of the feedback between groundnut and PGPRs and the need for variety-specific selection of PGPRs to improve inoculation success in groundnut. According to this study, it would be beneficial to promote the use of the isolates that perform well with the groundnut varieties.

Conclusion

The demand for microbial inoculants is growing, driven by the need for sustainable and environmentally friendly agricultural practices and safer and healthier food. In order to select the best Plant Growth Promoting Rhizobacteria (PGPR) inoculants for Senegalese groundnut varieties, we hypothesized that the response of groundnut to PGPR inoculation is variety-dependent and that there is a different degree of variability between traditional and modern varieties. The results of this study showed the efficacy of the inoculated strains in promoting the growth and yield parameters of groundnut varieties. However, this study revealed that the response of the groundnut to the bacterial inoculation was highly dependent on the variety considered. Although Fleur 11 and 55-437 were positively affected in some treatments, the varieties Essamay, Amoul Morom and Sunu Gaal responded better to the PGPR inoculation, especially regarding the biomass production and yield parameters, demonstrating the differential feedback between groundnut genotypes and PGPR partners. These results indicated that the functional variation among the inoculated bacteria and the groundnut varieties is crucial for establishing potential formulations of microbial inoculants to improve groundnut productivity. The increases in groundnut plant productivity for some varieties should be considered as new promising data for further adoption of microbial inoculation for groundnut improvement.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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