

## Responses of Soybean (*Glycine Max* (L.) Merrill) to Inoculation with *Bradyrhizobium japonicum* According to Soil Type in Southeastern DR Congo

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### Abstract

This study evaluates the impact of soybean inoculation with *Bradyrhizobium japonicum* on different soil types (Acric Ferralsol, Xanthic Ferralsol, Eutric Cambisol) in the Lubumbashi region, in southeastern DR Congo, where yields are low due to soil degradation and limited use of inputs. The main objective was to identify the optimal combinations between *Bradyrhizobium* strains, soybean varieties, and soil types in order to improve soybean productivity and contribute to the regeneration of degraded tropical soils. A field trial was conducted using a split-plot design. Three strains of *Bradyrhizobium japonicum* and an uninoculated control were applied to five soybean varieties on three different soil types. The seeds were inoculated before sowing. Agronomic data (emergence, growth, nodulation, yield) and soil physicochemical properties were collected and analyzed by ANOVA to evaluate the effects of different factors and their interactions. The results showed a strong interaction between soil type, *Bradyrhizobium* strain, and soybean variety. The Ferralsols, more degraded, responded better to inoculation than the eutric Cambisol, which is more fertile. Strains S1 (USDA 110) and S3 (USDA 142) proved to be the most effective in improving nodulation and vegetative growth. Surprisingly, the highest yields were observed in the acric Ferralsols, despite lower nodulation, suggesting a better allocation of resources toward seed production. Inoculation also had a positive effect on pH and cation availability in Ferralsols. The study confirms that the effectiveness of soybean inoculation strongly depends on local soil conditions. An agroecological approach, adapting the choice of *Bradyrhizobium* strains to the soil type, is essential for sustainably improving soybean productivity and the fertility of tropical soils.

**Keywords:** *Glycine max* (L.) Merrill, *Bradyrhizobium japonicum*, Ferralsols, Cambisol, inoculation, yield.

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### INTRODUCTION

Soybeans (*Glycine max* (L.) Merrill) are a strategic crop worldwide due to their high protein content and their diverse uses in human and animal nutrition. In sub-Saharan Africa (SSA), production has increased

significantly, rising from approximately 20,000 ha in the 1970s to over 1,500,000 ha in 2016 (Khojely et al., 2018). However, this expansion of acreage has not been accompanied by a comparable improvement in yields, which remain low, at around 1.1 t·ha<sup>-1</sup> compared to a

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world average of 2.4 t·ha<sup>-1</sup> (Khojely *et al.*, 2018). This situation results in particular from the use of low-performing varieties, soil degradation and limited adoption of fertilizers and rhizobial inoculants (Woomer *et al.*, 2012).

Tropical soils in Africa are characterized by low fertility, exacerbated by erosion, acidity, low cation exchange capacity, and nutrient depletion (Bado, 2002 ; Raimi *et al.*, 2017 ; Hassan, 2018 ; Jaiswal *et al.*, 2021. In a context of rising mineral input costs and environmental challenges, rhizobial symbioses appear as a sustainable alternative (VERICELet *et al.*, 2010). Among them, the association between soybeans and *Bradyrhizobium japonicum* is particularly effective for biological nitrogen fixation, promoting growth, soybean productivity and soil enrichment (Smith *et al.*, 1987; Gopalakrishnan *et al.*, 2015; Kasu-Bandi *et al.*, 2021). These mechanisms prove essential in regions such as Haut-Katanga, where Ferralsols and Cambisols often exhibit low levels of fertility.

However, the response of soybeans to inoculation varies greatly depending on the bacterial strain, variety, and soil properties (Mukalay, 2016 ; Tshibuyi *et al.*, 2019 ; Kyei-Boahen *et al.*, 2023). The acidic and nutrient-poor soils of the DRC, particularly the acrid and xanthic Ferralsols of Haut-Katanga, impose significant limitations on nodulation and nitrogen fixation, due in particular to competition from inefficient indigenous strains, low levels of available phosphorus, or excessively low pH (Thies *et al.*, 1991 ; Richardson *et al.*, 2009 ; Nyoki, 2014). Conversely, more fertile soils such as certain Cambisols can reduce symbiotic engagement when nutrients are abundant (Denison *et al.*,

2004 ; Graham, 2008 ; Reid *et al.*, 2011), highlighting the need for differentiated inoculation strategies (Nguyen *et al.*, 2020).

Thus, this study aims to analyze the cross effect of *Bradyrhizobium japonicum* strains and soybean varieties on three soils representative of Haut-Katanga (Ferralsol acrique, Ferralsol xanthique, Cambisol eutrique), in order to identify the optimal soil-strain-variety combinations to improve soybean productivity and contribute to the regeneration of tropical soils.

## ENVIRONMENT AND METHODS

### Study environment

The soils of Lubumbashi and its surroundings are of polygenic origin and derive mainly from the Precambrian basement of the Lubumbashi syncline, dominated by the shales of the Kundelungu series. They are characterized by a high clay content, a low cation exchange capacity (CEC < 16 cmol·kg<sup>-1</sup>, kaolinite), and are rich in iron and aluminum sesquioxides. The average pH of the water is approximately 5.2, indicating marked acidity (Kasongo *et al.*, 2013). The local climate is classified as CW6 according to Köppen, with a rainy season from November to March and a dry season from May to September. Average annual rainfall reaches 1270 mm, with extreme values ranging from 717 to 1770 mm, and the average annual temperature is around 20 °C. (Kasongo *et al.*, 2013 ; Louis *et al.*, 2015 ; Tshibuyi *et al.*, 2019). The ombrothermic diagram (Figure 1) highlights seasonal variations in potential evapotranspiration (PET) and temperatures, providing key information for interpreting climatic processes influencing crop growth in the region.

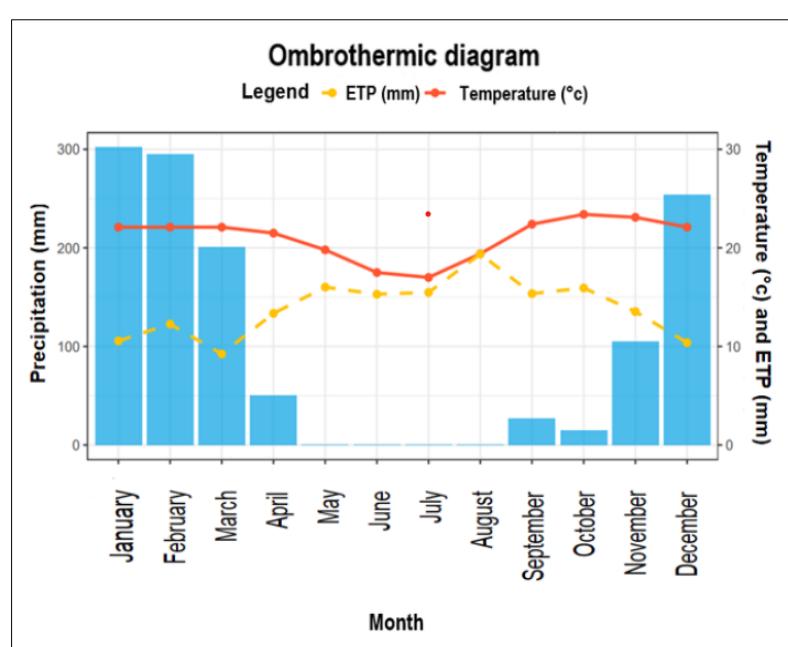


Figure 1: Ombothermic diagram ETP : Potential evapotranspiration (Climate data from the Luano airport meteorological station)

### Description of the soils at the experimental sites

The experiments were conducted at three sites with distinct altitudes and vegetation types. The Kanyameshi station (1303 m) is dominated by *Tithonia diversifolia* and *Hyparhenia rufa*. The Eliora farm site (1190 m) is characterized by a wooded savanna, while the Katandula farm (1224 m) is distinguished by a grassy savanna dominated by *Hyparhenia rufa* (Figure 2).

*Tithonia diversifolia* and *Hyparhenia rufa*. The Eliora farm site (1190 m) is characterized by a wooded savanna, while the Katandula farm (1224 m) is distinguished by a grassy savanna dominated by *Hyparhenia rufa* (Figure 2).

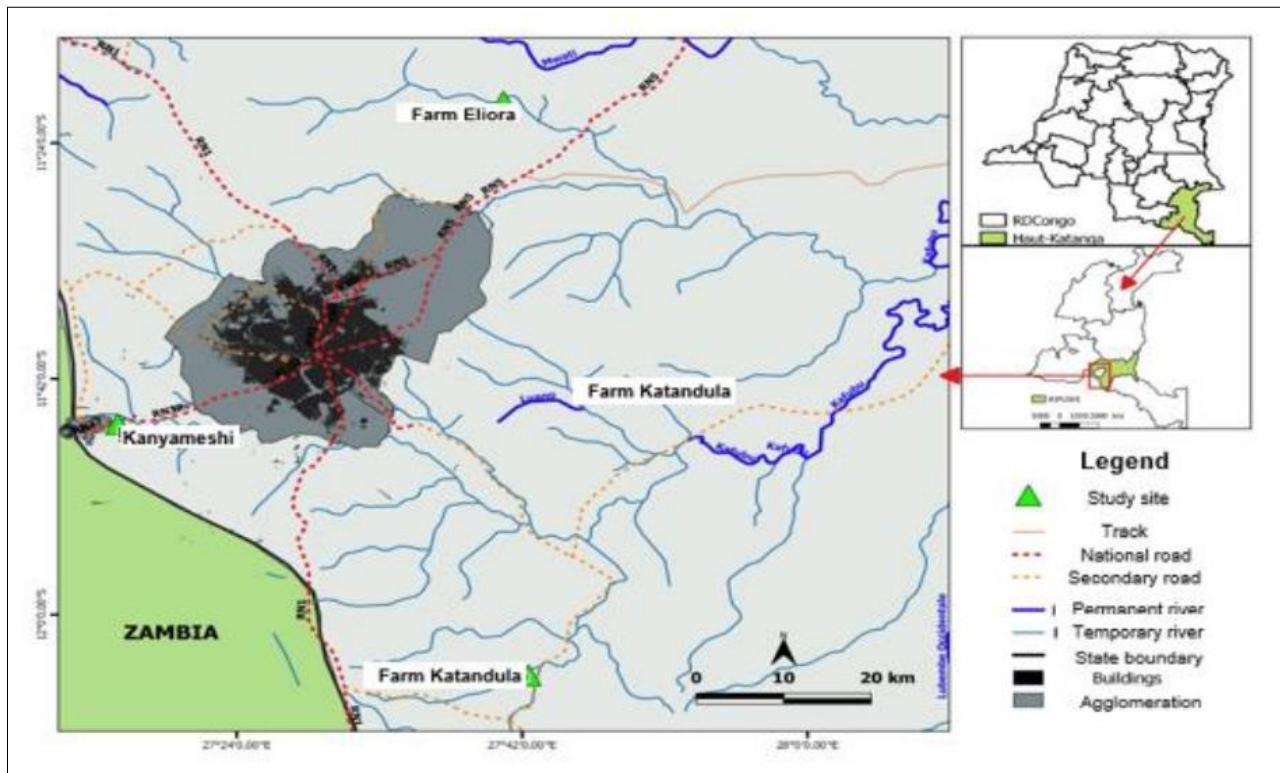


Figure 2: Location of experimental study sites

## METHODOLOGY

### Study sites

The study was conducted using a split-plot design to evaluate the effect of three strains of *Bradyrhizobium japonicum* compared to an uninoculated control on five soybean varieties (*Glycine max* (L.) Merrill). Each strain-variety combination was replicated three times per site, resulting in twenty treatments. The experimental design and analysis were conceived according to Dagnelie (2012) and the recommendations of Montgomery (2017).

### Plant material and inoculants

Five soybean varieties were used: Pka06 (V1) and Imperial (V2) from INERA Mulungu (Bukavu), SAFARI MX (V3) and KAFUE (V4) from SEED CO (Zambia), and the local variety TGX1893-10F (V5) from INERA KIPopo. Three strains of *Bradyrhizobium japonicum* (USDA strains) from the Agricultural Research Service (NRRL, USA) were tested.

### Sowing and inoculation

Sowing was carried out at a spacing of 0.40 × 0.20 m (density ≈ 375,000 plants·ha<sup>-1</sup>), with three seeds per hill. Seed inoculation was performed according to a standardized protocol: preparation of a sugar adhesive (120 g sugar/250 ml lukewarm water), moistening of 10

kg of seeds, addition of 100 g of inoculum, and homogenization to ensure coating. The seeds were dried in the shade (~10 min) and then sown rapidly in moist, prepared soil, with the exception of uninoculated control plots.

### Soil sampling

Soil samples were collected at the flowering stage (~50% flowering) from the rhizosphere of plants in the central rows, using a hand auger in the 0–20 cm layer, in accordance with Moreira *et al.* (2012). Five planting holes per plot were sampled, the roots slightly uprooted; the rhizosphere was shaken into labeled bags, air-dried, sieved to 2 mm and shipped to the laboratory.

### Physico-chemical analyses (ZARI laboratory)

The analyses were carried out at the Soil Fertility Laboratory (ZARI, Mt. Makulu, Lusaka). The following parameters were measured using standard methods: pH (1 M KCl), exchangeable acidity ( $\text{Al}_3^+$ ,  $\text{H}^+$ ) by KCl extraction, organic carbon (potassium dichromate), total nitrogen (Kjeldahl method), mineral forms  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$  (KCl extraction), available phosphorus (extraction + spectrophotometry), exchangeable cations (Ca, Mg by AAS; K, Na by flame photometry), and cation exchange capacity (CEC). The methods and protocols used comply with current

references and standards (Black *et al.* (1965); Bray RH *et al.*, 1945; Kalra *et al.*, 1991; McKeague, 1978; Motomizu *et al.*, 1983); Potash and Phosphate Institute (1979); Richards, 1954).

### Agronomic and biological measures

Symbiotic efficiency was assessed according to four groups of variables: emergence rate (estimated from 50% germination), vegetative growth (stem height and diameter at the collar measured on 5 random plants at the beginning of flowering), nodulation (total number of nodules and active nodules assessed by incision and internal staining) and yield components (number of pods/plant, weight of 1000 seeds, yield extrapolated to ha after harvest, threshing and winnowing).

### Analyses

The collected data were subjected to a three-way ANOVA to assess the effects of soil type, *Bradyrhizobium japonicum* strains, and soybean varieties on the measured parameters. Post-hoc LSD tests were applied to differentiate means in cases of significant differences, with a significance level set at 5%. The analysis was performed using R 4.0.3 software. The specific effects of strain-variety interactions were explored separately for each soil type to assess the specific behaviors of the soils in relation to the other factors (varieties and strains).

## RESULTS

### Variability of soybean vegetative parameters according to *Bradyrhizobium japonicum* strains and soil types: Results of the analysis of variance

Analysis of variance (ANOVA) shows that soybean vegetative, nodulation, and yield parameters are strongly influenced by soil type, variety, and, in some cases, their interaction with *Bradyrhizobium japonicum* strains. Emergence rate (Figure 3a) is significantly affected by soil and variety, with both soil  $\times$  strain and soil  $\times$  variety interactions. Eutric Cambisol and strain S3 exhibit the best performance, while TGX-1893-10F shows the lowest values. Collar diameter (Figure 3b) also depends on soil and variety, with a soil  $\times$  strain interaction, the largest diameters being observed on Xanthic Ferralsol. Plant height (Figure 3c) is influenced by soil, variety, and all interactions, including the triple interaction, revealing complex combined effects. Fresh biomass (Figure 3d) is determined primarily by soil and variety, with soil  $\times$  strain and soil  $\times$  variety interactions, the best combination being Xanthic Ferralsol–S3–Pka 06. Leaf area (Figure 3f) depends on soil and variety but is not affected by strain. For nodulation (Figures 3e–3g), no isolated effect is observed, but the triple soil  $\times$  strain  $\times$  variety interaction is significant, with strains S1–S3 improving nodulation compared to the control. Regarding fruiting (Figures 3h–3j), the number of pods and the 100-seed weight are influenced by soil, variety, and certain interactions, with fertile soils and strains S1–S3 improving these parameters, while yield per hectare is not significantly affected by any factor, suggesting a strong influence of uncontrolled external conditions.

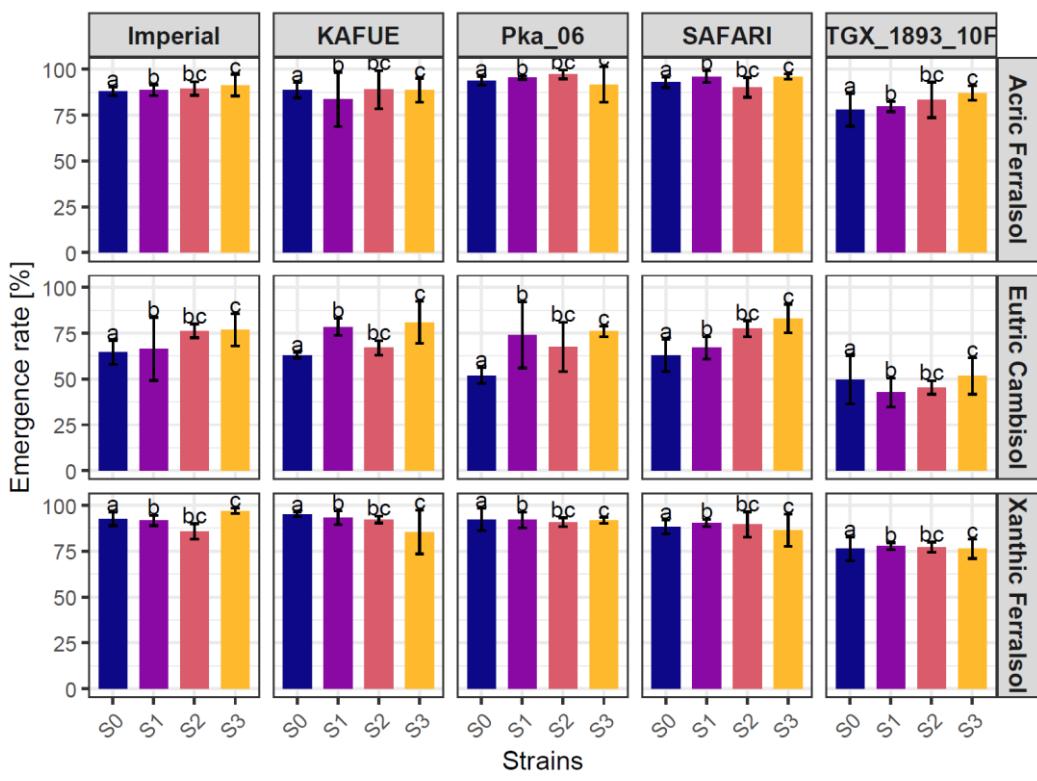


Figure 3a

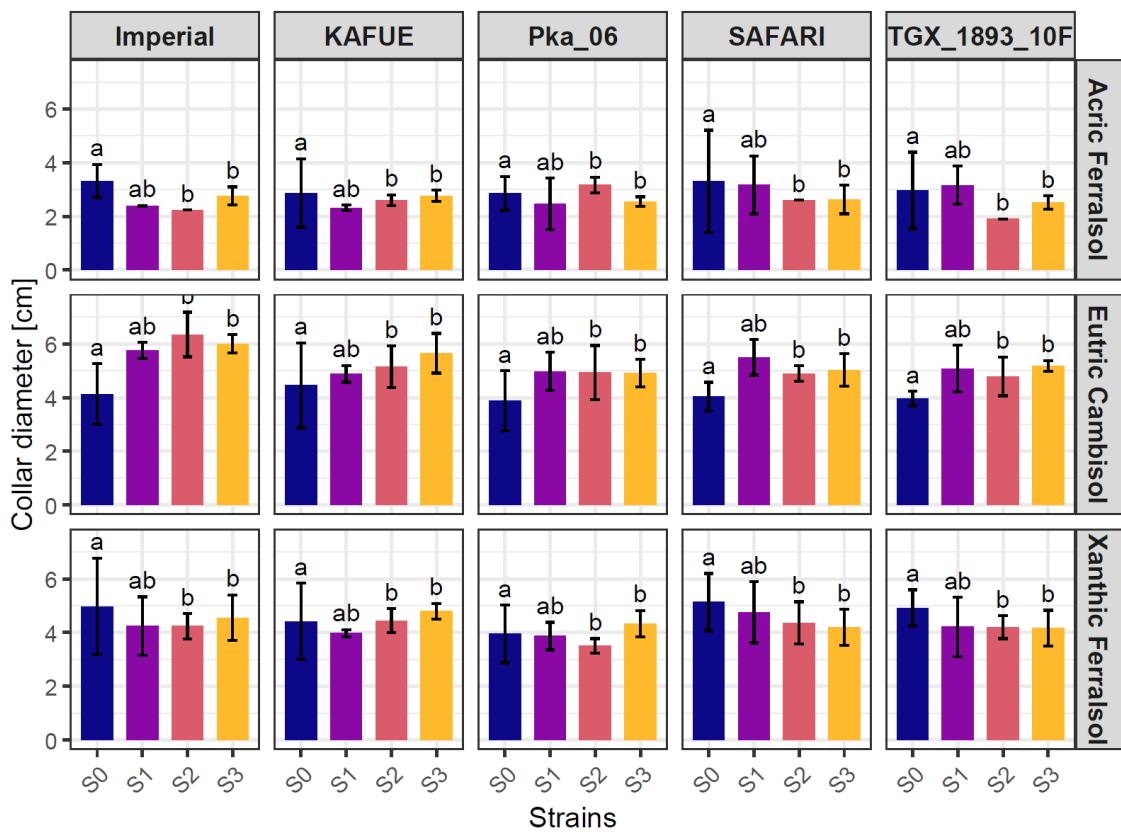


Figure 3b

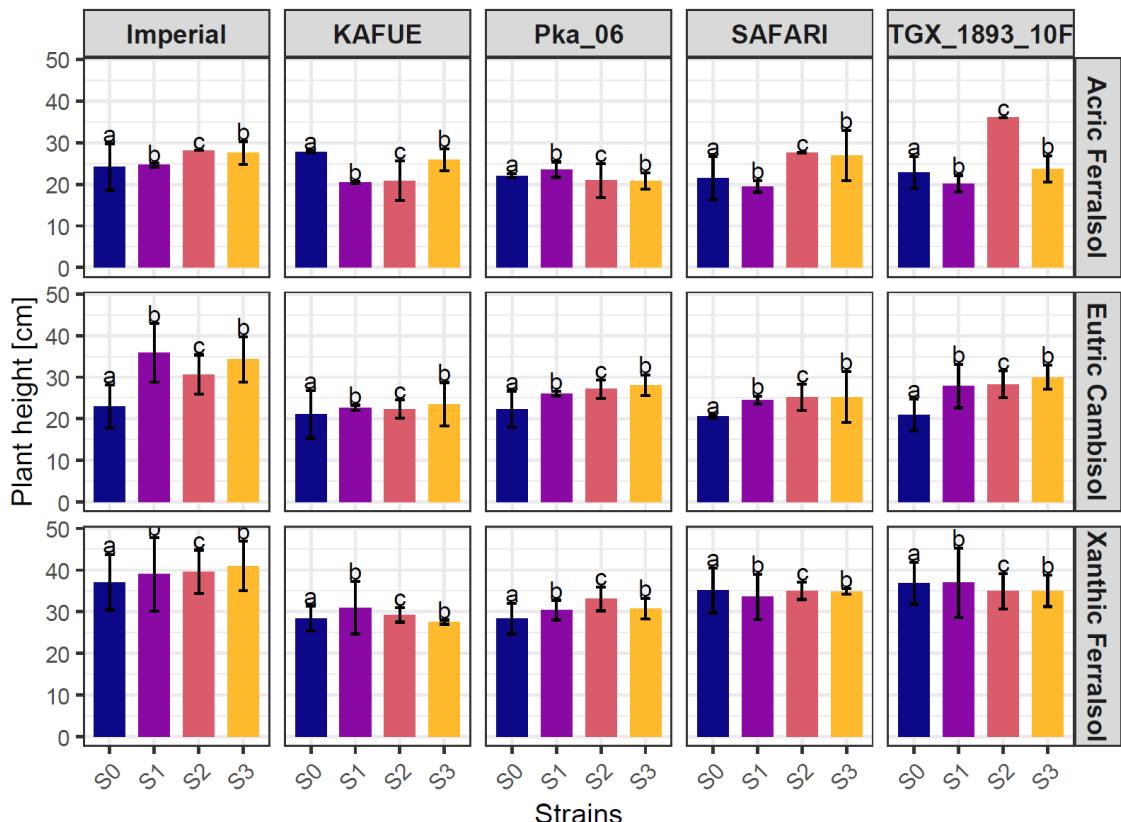


Figure 3c

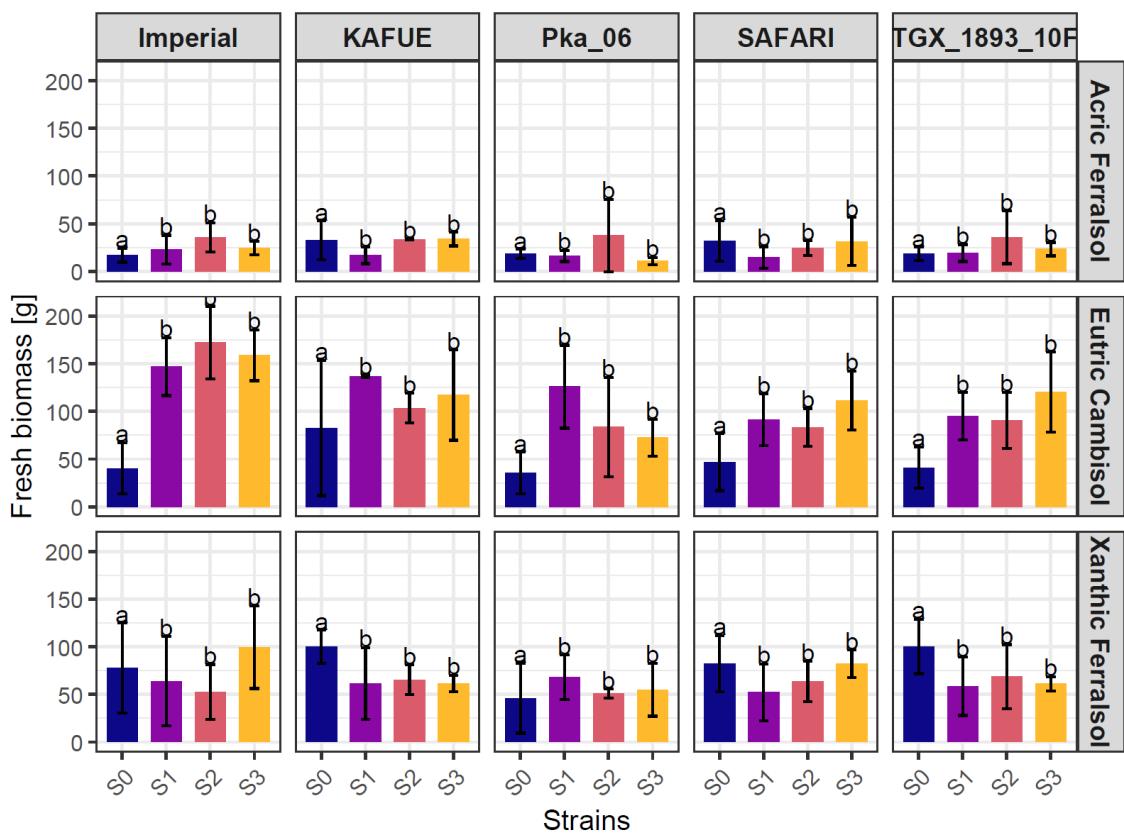


Figure 3d

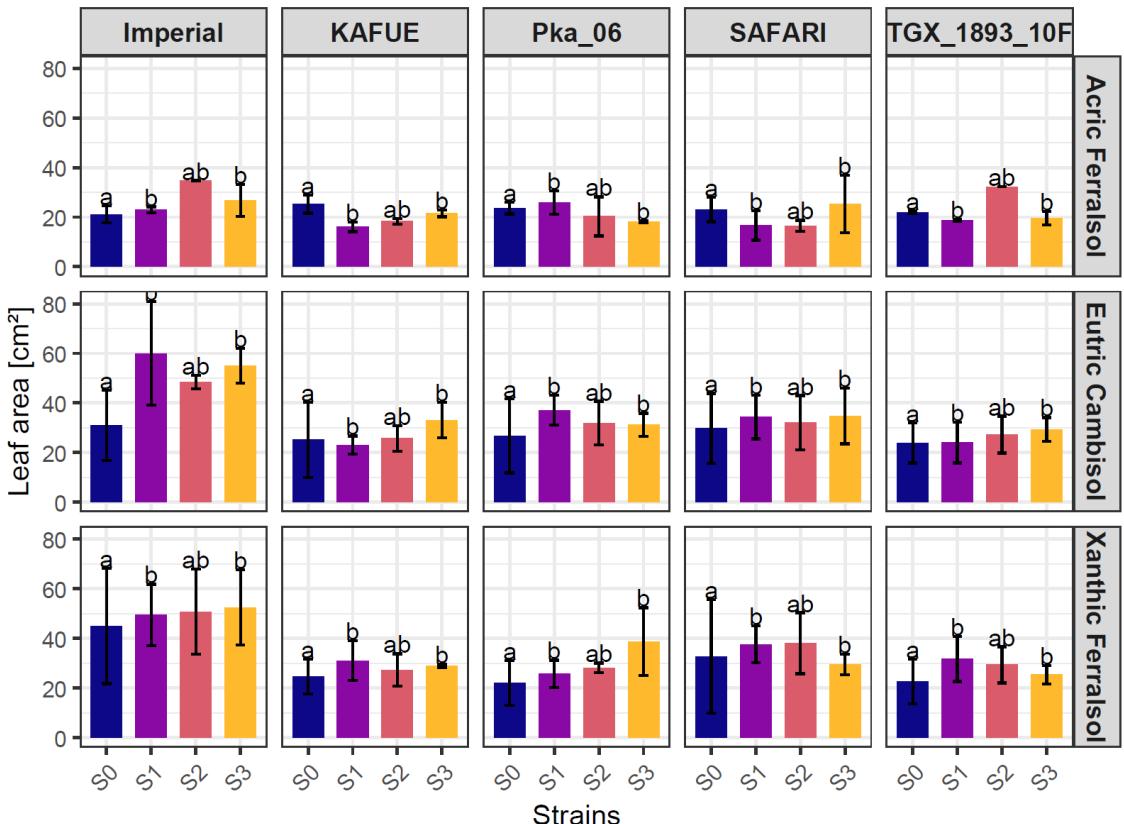


Figure 3e

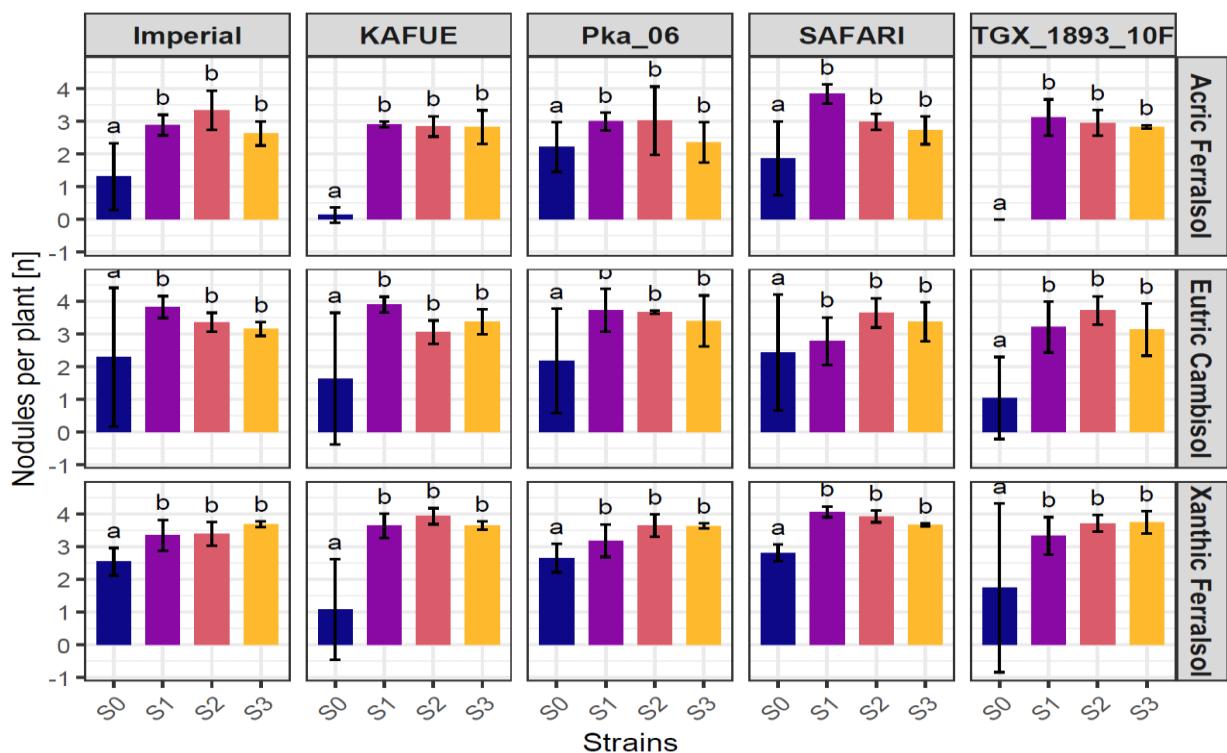


Figure 3f

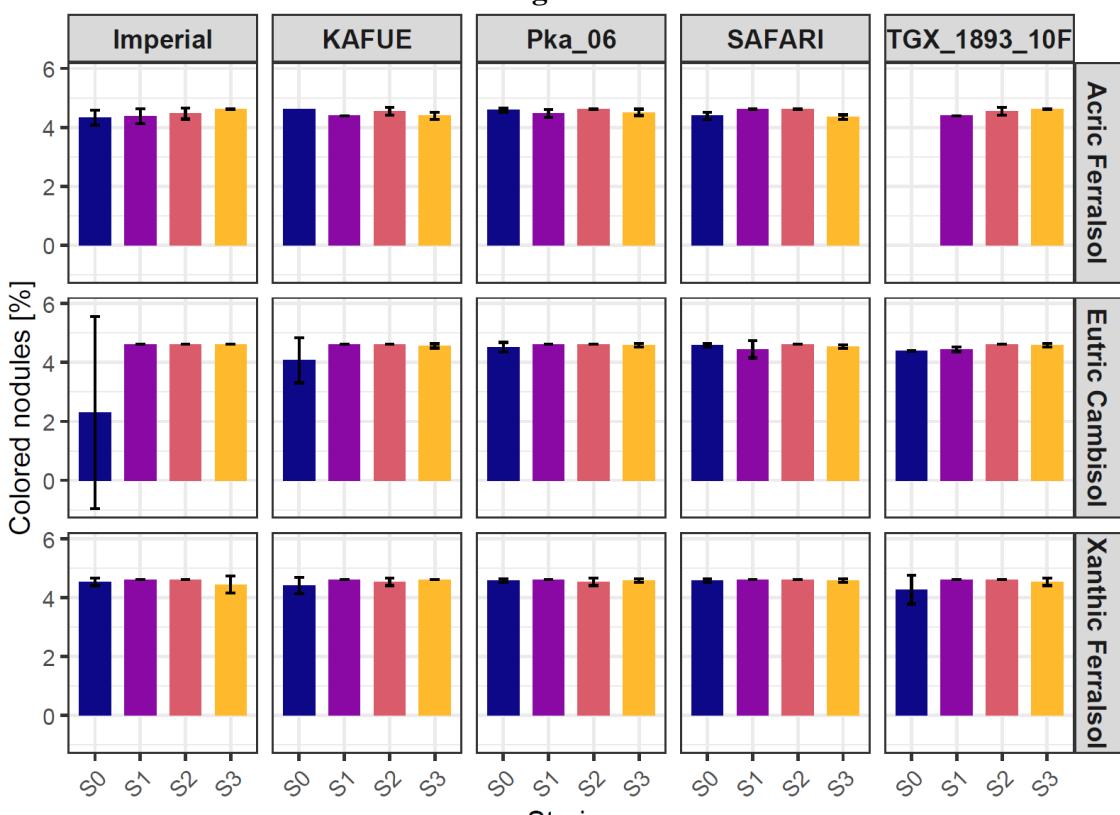


Figure 3g

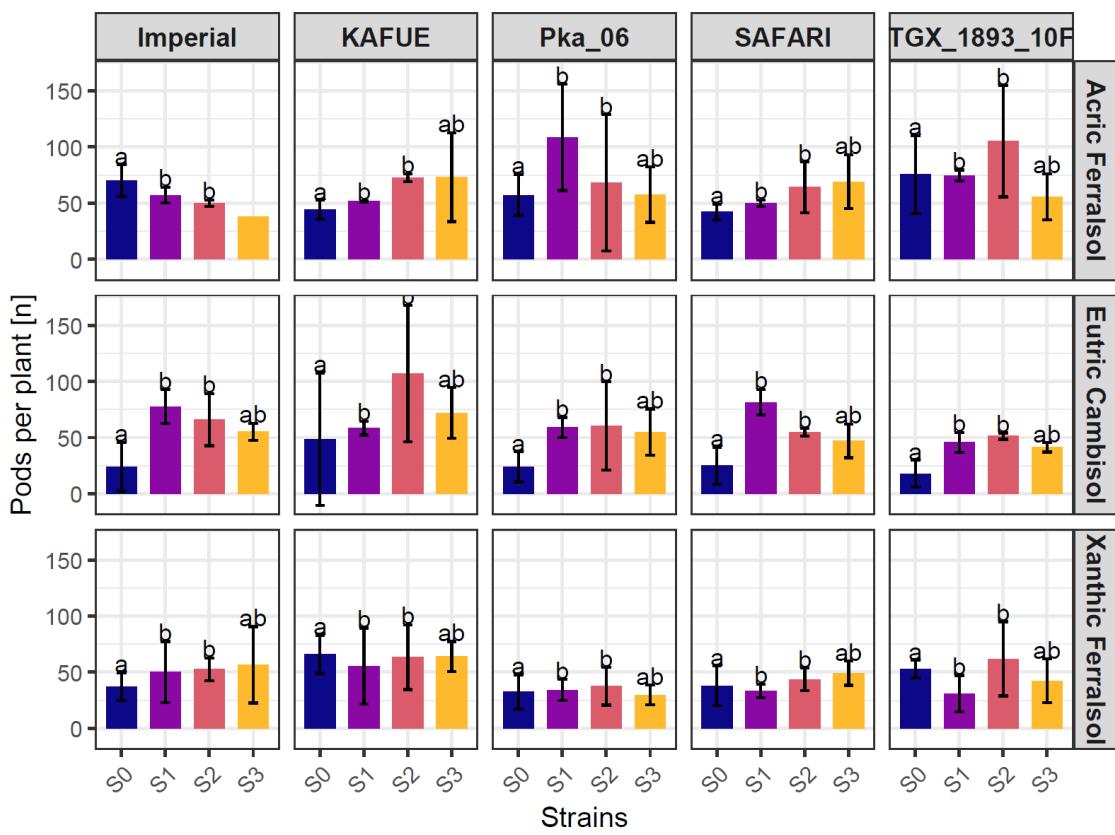


Figure 3h

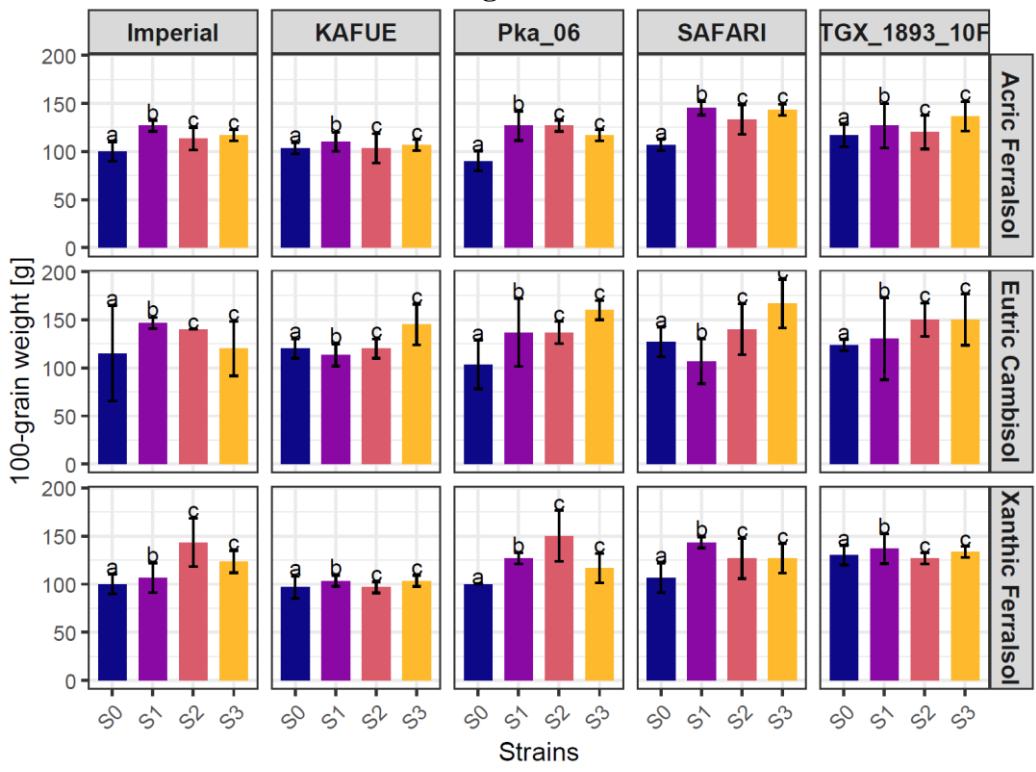


Figure 3i

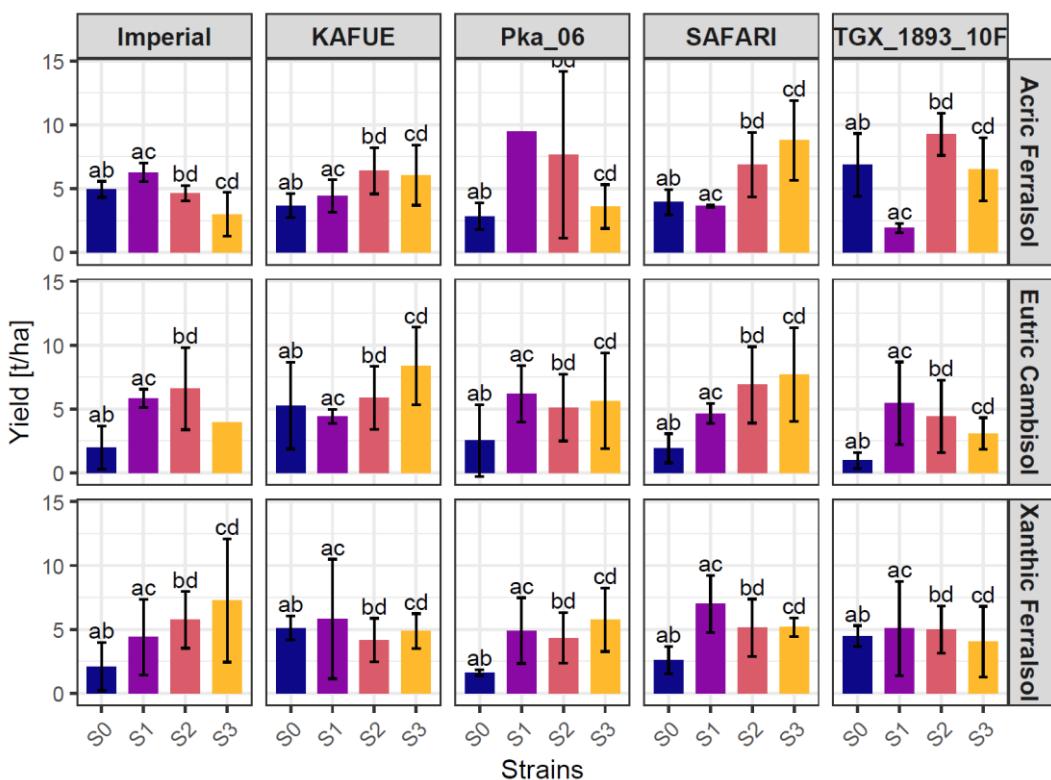


Figure 3j

**Figure 3: Relationships between the agronomic performance of different soybean varieties and strains of *Bradyrhizobium japonicum* (S1 : USDA 110, S2: USDA 136 and S3: USDA 142) according to soil type : a) Emergence rate ; b) Collar diameter ; c) Plant height; d) Fresh biomass ; e) Leaf area ; f) Number of nodules per plant ; g) Number of colored nodules per plant ; h) Number of pods per plant ; i) Weight of 100 seeds ; j) Yield (t/ha)**

#### Correlation between vegetative parameters, soybean yields and the physicochemical characteristics of different soil types in Lubumbashi

The positive correlations observed between soil chemical properties and soybean morpho-physiological traits ( $p < 0.001$ ) highlight the major importance of chemical fertility for vegetative performance. Parameters such as calcium (Ca), cation exchange capacity (CEC), base saturation, and pH are positively associated with plant height, collar diameter, aboveground biomass, leaf area, and nodule number, contributing to mineral nutrition, cell structure, physiological signaling, and the establishment of symbiosis with *Bradyrhizobium*.

Conversely, soil acidity and, unexpectedly, total and available phosphorus levels are negatively correlated

with growth and yield parameters. This paradox can be explained by the fixation of phosphorus in acidic soils as Fe-P or Al-P complexes, making it less available to plants despite its apparent presence.

The lack of significant correlations with grain yield highlights a decoupling between vegetative growth and final productivity. This indicates that, even with fertile soil, production is highly dependent on abiotic factors (water stress, temperature, light) and biotic factors (pathogens, pests), particularly during the reproductive phase. These results underscore the importance of an integrated crop management approach to optimize soybean yield.

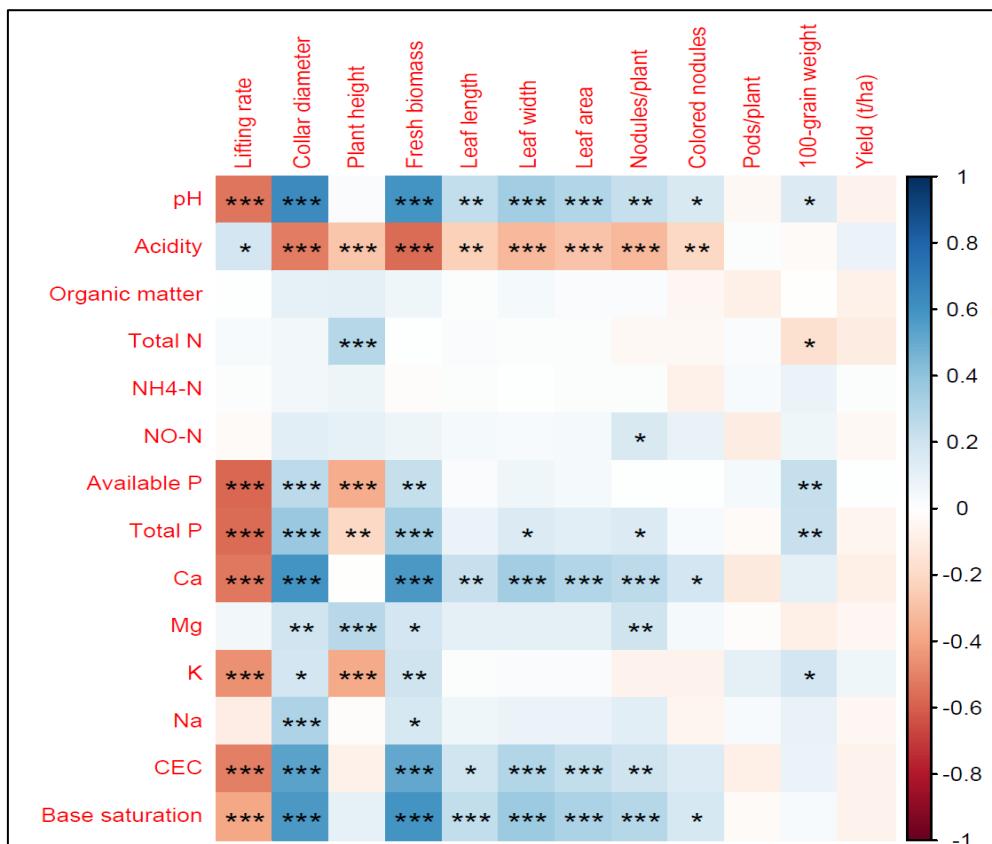


Figure 4: Pearson correlation between vegetative parameters, soybean yield and physico-chemical parameters of soils

#### Influence of *Bradyrhizobium japonicum* strains on soil chemical parameters

Comparative analysis of soil chemical properties between plots inoculated with different strains of *Bradyrhizobium japonicum* (S1, S2, S3) and the uninoculated control plot (S0) reveals a limited influence of bacterial inoculation on soil chemistry. Indeed, soil pH showed no significant variation between the different treatments in the three soil types studied (Table 1), suggesting short-term stability of this property, independent of inoculation.

Regarding available phosphorus, inoculated and uninoculated plots showed similar levels in eutric (loamic) Cambisols and acrid (vetic) Ferralsols. However, an exception was observed in xanthic (vetic) Ferralsols, where inoculation with strain S2 was

associated with a significant decrease in available phosphorus compared to the control plot. This result indicates an indirect effect of the strain on phosphorus dynamics, potentially linked to specific microbial interactions or increased phosphorus mobilization by the plant. Nevertheless, total phosphorus levels remained unchanged regardless of the treatment applied.

Furthermore, other soil chemical properties, including total nitrogen, mineral forms of nitrogen ( $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N), cation exchange capacity (CEC), organic matter, and base saturation, were not significantly influenced by the application of the different *Bradyrhizobium* strains. These results show that, under the study conditions, inoculation did not significantly alter the main soil chemical properties.

Table 1: Chemical properties of the soil at flowering according to different soil types and strains of *Bradyrhizobium japonicum*

Floors	Strains	pH KCl	Available-P	Total-P	Total-N	NH4-N	NO3-N	CEC	Organic Matter	Base Saturati on
Eutric (loamic) cambisols	S0	4.6±0.1	4.7 ± 0.6 abc	217.3±7.6	0.24 ± 0.01 c	4.8±0.2	23.6±1.2	6.7±0.4	2.7-0.2	105-0.5
	S1	4.5±0.2	5.4±1 abc	210.7±9.1	0.21 ± 0.01 abc	4.8±0.3	24.2±1.7	6.8±0.5	2.3-0.2	102.3-1.7
	S2	4.4±0.1	3.7±0.6 a	216.7±6.7	0.2 ± 0.01 abc	4.7±0.3	21.6±1	5.6±0.2	2.3-0.2	103.6-0.5
	S3	4.4±0.1	3.8±0.3 ab	214.7±7.7	0.22 ± 0.01 bc	4.9±0.3	20.7±1.3	6.8±0.3	2.5-0.1	104.5-0.5
<b>Mean</b>		<b>4.5±0.1 B</b>	<b>4.4 ± 0.3 A</b>	<b>214.8±3.8 A</b>	<b>0.22±0 B</b>	<b>4.8±0 .1</b>	<b>22.5±0 .7</b>	<b>6.5±0.2 B</b>	<b>2.5-0.1 B</b>	<b>103.8-0.5 B</b>
	S0	4.2±0.2	7.3±0.8 bc	217.3±8.9	0.18±0.01 ab	5±0.4	19.8±1.2	5.9±0.4	1.8-0.3	86.1-5.3
	S1	4±0.1	7.7±0.8 c	230±12.2	0.18±0.01 abc	5±0.2	20.2±1.5	5.1±0.5	1.9-0.3	89.9-2.6

Ferralsols acriques (Vetic)	S2	4±0.1	8.4±1 c	230.7±12.9	0.2 ± 0.01 abc	5.9±0.7	21.7±1.6	5.2±0.4	1.9-0.3	85.7-4.4
	S3	3.8±0	6.3±0.7 bc	204.7±6.3	0.22 ± 0.02 abc	4.8±0.5	24.3±2.3	4.7±0.3	2-0.3	78.9-3.7
<b>Mean</b>	<b>4±0.1 A</b>		<b>7.4±0.4 B</b>	<b>220.5±5.2 A</b>	<b>0.19 ± 0.68 A</b>	<b>.2</b>	<b>5.2±0 .9</b>	<b>21.5±0 A</b>	<b>5.2 ± 0.2 A</b>	<b>1.9-0.1 A</b>
<b>Xanthic Ferralsols ls (Vetic)</b>	<b>S0</b>	<b>5.6±0.1</b>	<b>54.3±3.5 e</b>	<b>662±61.4</b>	<b>0.2 ± 0.01 abc</b>	<b>5.7±1</b>	<b>22.1±2</b>	<b>10.2±0.5</b>	<b>2.2-0.2</b>	<b>106.4-0.6</b>
	<b>S1</b>	<b>5.6±0.1</b>	<b>37.3±4.8 de</b>	<b>591.3±54.1</b>	<b>0.17±0.02 abc</b>	<b>4.6±0.3</b>	<b>19.5±1.3</b>	<b>9.6±0.2</b>	<b>2.2-0.2</b>	<b>105.6-0.2</b>
	<b>S2</b>	<b>5.4±0.2</b>	<b>29±4 d</b>	<b>498±45.6</b>	<b>0.14±0.02 a</b>	<b>5.5±0.4</b>	<b>24.9±1.7</b>	<b>8.5±0.6</b>	<b>2-0.2</b>	<b>105.3-0.3</b>
	<b>S3</b>	<b>5.7±0.1</b>	<b>39.1±3.3 de</b>	<b>610±45.8</b>	<b>0.13±0.02 a</b>	<b>5±0.3</b>	<b>24.4±1.8</b>	<b>9.7±0.3</b>	<b>2.1-0.2</b>	<b>105.6-0.2</b>
<b>Mean</b>	<b>5.6 ± 0.1 B</b>		<b>39.9±2.3 C</b>	<b>590.3±26.5 B</b>	<b>0.16±0.0 1 A</b>	<b>5.2±0 .3</b>	<b>22.7±0 .9</b>	<b>9.5±0.2 C</b>	<b>2.1-0.1 AB</b>	<b>105.7-0.2 C</b>
S0	4.8-0.1		22.1-3.6 b	365.6-37.6	0.205- 0.007	5.1±0 .4	21.8±0 .9	7.6±0.4 b	2.3-0.1	99.1-2.2
S1	4.7-0.1		17-2.8 ab	346.6-32.7	0.188- 0.008	4.8±0 .2	21.3±0 .9	7.2±0.4 ab	2.1-0.1	99.5-1.4
S2	4.6-0.1		13.7-2.1 a	315.1-25	0.178- 0.01	5.3±0 .3	22.7±0 .8	6.4 ± 0.3 a	2.1-0.1	98.2-2
S3	4.7-0.1		16.4-2.7 ab	343.1-32.3	0.188- 0.011	4.9±0 .2	23.1±1 .1	7.1±0.3 ab	2.2-0.1	96.3-2.2
Ground	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	0.963	0.2095	0	<b>0.00228</b>	<b>0</b>	
Strains	0.419	<b>0.0184</b>	0.774	0.2797	0.55	0.3935	<b>0.0148</b>	0.73582	0.0688	
Variety	0.94	0.406	0.686	0.1228	0.721	0.4921	0.2629	0.77254	0.2697	
Sites : Strains	0.433	<b>0.0133</b>	0.339	<b>0.0182</b>	0.62	0.0758	0.356	0.88534	0.4983	
Sites : Variety	0.768	0.2087	0.656	0.772	0.714	0.7498	0.3965	0.64581	0.0795	
Strains : Variety	0.996	0.9627	0.983	0.9867	0.934	0.3965	0.9718	0.89464	0.8941	
Sites : Strains: Variety	0.999	0.5226	0.637	0.9764	0.716	0.9883	0.9269	0.69130	0.9291	

## DISCUSSION

### Influence of soil type and tree stumps *Bradyrhizobium japonicum* on the productivity and agro-physiological parameters of soybeans

The study results confirm that the interaction between soil types, *Bradyrhizobium japonicum* strains, and soybean varieties significantly influences vegetative growth, nodulation, and soybean productivity in the tropical context of Haut-Katanga. This synergistic interaction between soil, genotype, and inoculant was also highlighted by Solomon *et al.* (2012) and Tshibuyi *et al.* (2019).

From a pedological point of view, unlike acrid Ferralsols, xanthic Ferralsols and eutric Cambisols allowed better vegetative growth (height, collar diameter, biomass), linked to a more favorable chemical composition: moderate pH, more available phosphorus and calcium (Mukalay, 2016; Tetteh *et al.*, 2017). These observations corroborate the work of (Laurent *et al.*, 1998; Argaw *et al.*, 2014; Temegne *et al.*, 2015; olive, *et al.*, 2019) according to which the low availability of phosphorus, often linked to its fixation by iron and aluminum oxides, constitutes a major constraint in acidic tropical soils.

Regarding nodulation, strain USDA 110 (S1) proved particularly effective, especially on eutric Cambisols, which confirms the observations of Woomer *et al.* (2012) and Giller *et al.* (2011) on strain-soil specificity in terms of symbiotic efficacy. The color and size of the nodules, recognized as functional indicators, are well documented by oliveet *al.* (2019). Conversely,

acrid Ferralsols, characterized by excessive acidity, exhibited reduced nodulation, a phenomenon largely attributed to the inhibitory effect of acidic pH (Chimdi *et al.*, 2022; Nyoki *et al.*, 2014).

A paradoxical result was observed, however: despite lower nodulation, the acrid Ferralsols generated the highest yields. This phenomenon could be explained by a redistribution of resources towards pod formation, as suggested by Solomon *et al.* (2012). Furthermore, certain strains such as S2 and S3 have shown variable effects on yields, highlighting the functional diversity of *Bradyrhizobium* strains (Okereke *et al.*, 2001 ; Abaidoo *et al.*, 2007).

Inoculation also led to an improvement in pH and exchangeable cation levels (Ca, Mg) in Ferralsols, reflecting the positive impact of rhizobial symbiosis on the regeneration of acidic soils via microbial activity. (Nyoki *et al.*, 2018; McCully, 2001; Lazali *et al.*, 2020). These results corroborate the work of Kebede (2021) and Wobeng *et al.*, (2020), which show that legumes, through biological nitrogen fixation and microbial stimulation, contribute to the sustainability of tropical soil fertility.

However, despite strong nodulation and increased vegetative growth, eutric Cambisol underwent a slight chemical regression. This decline could be explained by its initially high fertility, thus limiting the marginal response to inoculation (Nguyen *et al.*, 2020). Similar results were obtained by Księżak *et al.*, (2022), which highlight increased effectiveness of inoculation

when coupled with nitrogen fertilization, particularly in soils of moderate or low fertility.

In addition, several studies, including those of Lesueur *et al.* (1994) a Studies have shown that co-inoculation (e.g., with *Azospirillum*) or the use of amendments such as biochar or lime can significantly improve nodulation and productivity in acidic soils. This supports the integrated and localized optimization approach to symbiotic performance in soybeans.

Finally, beyond biological and chemical factors, the success of inoculation depends heavily on soil conditions and agricultural practices (Revellin *et al.*, 1996) These results highlight the need for an integrated agro-ecological approach, combining inoculant management, targeted fertilization and improvement of soil physical and chemical properties, to promote sustainable soybean productivity in sub-Saharan Africa (Dugué *et al.*, 2024).

#### **Differential responses to inoculation depending on soil properties**

The results demonstrate that the response of soybeans to inoculation with *Bradyrhizobium japonicum* is closely dependent on the physicochemical characteristics of the soil, including pH, phosphorus (P) availability, nitrogen (N) content, and the presence of native rhizobial populations. These observations confirm the work of Richardson *et al.* (2009), Nyoki *et al.*, (2014) and KC *et al.*, (2019), which highlight the central role of these parameters in soybean nodulation and growth.

In eutric Cambisols, despite their initially high fertility, inoculation did not always lead to improved yield. This result supports the hypotheses of Denison *et al.*, (2004) and Graham (2008), according to which plants tend to limit their symbiotic associations when resources are sufficient, in order to optimize their energy metabolism.

The variability in response to inoculation between soil types can also be attributed to competition between introduced strains and native rhizobial populations. In tropical soils, the latter are often abundant but inefficient, which can limit the benefits of inoculation (Thies *et al.*, 1991; Rodríguez-Navarro *et al.*, 2011; Grönemeyer *et al.*, 2014). The success of inoculation therefore depends on the competitiveness of the strain, its persistence in the soil (Mendoza-Suárez *et al.*, 2021) and its ability to preferentially colonize nodules (Chibeba *et al.*, 2017).

Ferralsols, despite their nutrient deficiencies and acidity, showed a notable agronomic response after inoculation. These results confirm the potential of legumes to restore degraded soils. (Manyong *et al.*, 1996; Kasongo *et al.*, 2013), particularly through symbiotic nitrogen fixation and the input of organic matter via

biomass decomposition (Jensen *et al.*, 2020; Thapa *et al.*, 2021). Justes *et al.* (2014) They specify that the processes of complementarity and facilitation between plants promote the acquisition of resources, particularly in conditions of nutritional deficiency.

The effectiveness of inoculation also varies depending on the soybean genotype. Some cultivars show specificity in nodulation, while others adopt a free nodulation strategy (N'Gbesso *et al.*, 2010). This underscores the importance of the link between varietal selection and agronomic management, including the choice of the appropriate rhizobial strain. Furthermore, co-inoculation with mycorrhizal fungi can enhance synergistic effects on growth and nutrition, as shown by Cornet *et al.*, (1982) and Duponnois *et al.* (2013).

Finally, various abiotic factors such as phosphorus availability, organic matter, or nitrate levels influence the response to inoculation (Nápoles *et al.*, 2009). Beugre *et al.* (2013) have shown that inoculation is particularly effective in soils poor in native rhizobia.

In summary, the results obtained in Haut-Katanga are part of a broader body of scientific evidence demonstrating that inoculation cannot be approached uniformly. It must be considered within a systemic framework that takes into account soil type, the density and effectiveness of native strains, plant needs, and interactions with other microorganisms. In sub-Saharan African agricultural systems, legumes remain a strategic tool for improving soil fertility, provided that practices are adapted to local ecological realities (Van Zwieten *et al.*, 2015; Naudin, 2009; Alabouvette *et al.*, 2018).

#### **Legumes and the regeneration of tropical soil fertility: A lever for sustainability**

This study confirms that the response of soybeans to inoculation with *Bradyrhizobium japonicum* is modulated by the specific soil characteristics of Haut-Katanga, highlighting the need for differentiated management of agricultural practices. In the acrid and xanthic Ferralsols, characterized by high acidity and low nutrient availability, inoculation with effective strains such as S1 (USDA 110) and S3 (USDA 142) resulted in a significant improvement in soybean growth, accompanied by edaphic benefits: increased pH, enrichment in exchangeable cations, and improved phosphorus availability. These results are consistent with those of Lazali *et al.* (2020) and Matías-Ramos *et al.* (2023), which highlight the role of legumes in the regeneration of tropical soils.

Conversely, in eutric Cambisols, rich in native rhizobia, the effects of inoculation were limited, or even absent, when the microbial density exceeded the critical threshold of 100 cells/g of soil (Thies *et al.*, 1991). In this case, the intense competition for nodule colonization reduces the effectiveness of the introduced strains. An

alternative strategy would be to plant legumes at the end of the rotation to limit nutrient depletion while benefiting from residual effects on subsequent crops (Carsky *et al.*, 1997; Zoundji *et al.*, 2024).

The success of inoculation also depends on strain-plant compatibility, application methods, and soil biological quality, as shown by Lupwayi *et al.* (2006) and Lesueur *et al.* (1994). In tropical areas, where soils are often degraded and poor in organic matter, legumes play a central role: they restructure soils, improve water retention, and contribute to the sustainability of agroecosystems (Roose, 2007).

From an economic standpoint, the adoption of inoculation remains contingent on its perceived profitability. As noted Saint Macary *et al.* (1990), Despite its agronomic potential, its large-scale deployment depends on the cost-benefit ratio, the accessibility of inoculants and technical support for farmers.

The integration of legumes into cropping systems through rotation or association improves the sustainability of agro-ecosystems. Van Zwieten *et al.* (2015) and Guinet (2019) They point out that the nitrogen fixed biologically by these crops reduces dependence on chemical fertilizers and promotes more resilient agriculture. Furthermore, as suggested De França *et al.*, (1970) And Bado, (2002) Combining inoculation with other interventions, such as the application of natural phosphate or the correction of soil acidity, enhances its benefits.

Finally, although the positive effects of inoculation are well established for soybeans (Aliyu *et al.*, 2013; Razafintsalama *et al.*, 2022), Some uncertainties remain regarding the necessity of reinoculation at each cycle and the adaptability of this practice to other legumes. It is therefore essential to continue research to assess the persistence of strains in tropical soils and their integration into long-term microbial dynamics.

## CONCLUSION

In summary, this study highlights the crucial importance of interactions between soil type, *Bradyrhizobium japonicum* strain, and soybean variety in modulating agronomic performance and fertility regeneration dynamics in tropical soils. The results showed that inoculation efficacy varies significantly according to edaphic characteristics, particularly pH, phosphorus availability, and initial fertility, influencing nodulation, vegetative growth, and yield. Ferralsols, although poorer, benefited from progressive chemical improvement under the influence of effective strains, reflecting the potential of legumes to restore acidic soils. In contrast, fertile Cambisols exhibited a more moderate response to inoculation, suggesting biological saturation

or weak symbiotic activation in the presence of abundant resources. Thus, the agronomic response of soybeans to inoculation is neither uniform nor linear, but strongly dependent on the local pedological and biological context. These results highlight the need for targeted agroecological approaches, integrating the selection of adapted strains, a detailed knowledge of soils and reasoned planning of rotations, in order to promote sustainable and resilient agriculture in tropical environments.

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## REFERENCES BIBLIOGRAPHIQUES

- Abaidoo, R. C., Keyser, H. H., Singleton, P. W., Dashiell, K. E., & Sanginga, N. J. A. S. E. (2007). Population size, distribution, and symbiotic characteristics of indigenous *Bradyrhizobium* spp. that nodulate TGx soybean genotypes in Africa. *Applied Soil Ecology*, 35(1), 57-67.
- Alabouvette, C., & Cordier, C. (2018). Fertilité biologique des sols: des microorganismes utiles à la croissance des plantes. *Innovations Agronomiques*, 69, np.
- Aliyu, I., Yusuf, A. A., & Abaidoo, R. C. (2013). Response of grain legumes to rhizobial inoculation in two savanna soils of Nigeria.
- Anup K.C., et Ghimire A., (2019). Soil Quality Status in Different Region of Nepal. In D. G.
- KC, A., & Ghimire, A. (2019). Soil quality status in different region of Nepal. In *Soil Fertility Management for Sustainable Development* (pp. 81-99). Singapore : Springer Singapore.
- Argaw, A. (2014). Symbiotic effectiveness of inoculation with *Bradyrhizobium* isolates on soybean [*Glycine max* (L.) Merrill] genotypes with different maturities. *SpringerPlus*, 3(1), 753.
- Bado, B.V., (2002). Role of legumes on the fertility of tropical ferruginous soils in the Guinean and Sudanese areas of Burkina Faso. *Laval University, Quebec*.
- Beugre, F. G., N'gbesso, P. D. F. M., Ama-Abina, J. T., & Yoro, R. G. (2013). Influence d'un herbicide et de l'inoculation des semences sur la croissance du soja [*Glycine max* (L.) Merrill] cultive sur un sol gravillonnaire de plateau. *Agronomie Africaine*, 25(3), 221-229.
- Black, C. A., & Evans, D. D. (1965). Methods of soil analysis Agronomy. *Amer. Soc. Agron., Inc. Publisher, Madison, Wisconsin, USA*.
- Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil science*, 59(1), 39-46.
- Carsky, R. J., Abaidoo, R., Dashiell, K., & Sanginga, N. (1997). Effect of soybean on subsequent maize grain yield in the Guinea savanna zone of West Africa.

- Chibeba, A. M., Kyei-Boahen, S., de Fátima Guimarães, M., Nogueira, M. A., & Hungria, M. (2017). Isolation, characterization and selection of indigenous Bradyrhizobium strains with outstanding symbiotic performance to increase soybean yields in Mozambique. *Agriculture, ecosystems & environment*, 246, 291-305.
- Chimdi, A., Negasa, D., & Chala, G. (2022). Effects of rhizobium inoculation and P fertilizer levels on selected soil properties, yield, and yield components of faba bean (*Vicia faba* L.): The case of Abuna Gindeberat, west Shewa Zone, Ethiopia. *Applied and Environmental Soil Science*, 2022(1), 3635989.
- Cornet, F., & Diem, H. G. (1982). Etude comparative de l'efficacité des souches de Rhizobium d'*Acacia* isolées de sols du Sénégal et effet de la double symbiose Rhizobium-*Glomus* mosseae sur la croissance d'*Acacia holosericea* et *A. raddiana*. *BOIS & FORETS DES TROPIQUES*, 198, 3-15.
- Dagnelie, P. (2003). *Principes d'expérimentation : planification des expériences et analyse de leurs résultats*. Presses agronomiques de Gembloux.
- de França, G. E., & de Carvalho, M. M. (1970). Ensaio exploratorio de fertilizacao de cinco leguminosas tropicais em um solo de cerrado. *Pesquisa Agropecuária Brasileira*, 147-153.
- Denison, R. F., & Kiers, E. T. (2004). Why are most rhizobia beneficial to their plant hosts, rather than parasitic?. *Microbes and Infection*, 6(13), 1235-1239.
- Dugué, P., Andrieu, N., & Bakker, T. (2024). Pour une gestion durable des sols en Afrique subsaharienne.
- Duponnois, R., Ramanankierana, H., Hafidi, M., Baohanta, R., Baudoin, E., Thioulouse, J., ... & Prin, Y. (2013). Des ressources végétales endémiques pour optimiser durablement les opérations de réhabilitation du couvert forestier en milieu méditerranéen et tropical : exemple des plantes facilitatrices vectrices de propagation des champignons mycorhiziens. *Comptes Rendus. Biologies*, 336(5-6), 265-272.
- Giller, K. E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., & Tittonell, P. (2011). A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field crops research*, 124(3), 468-472.
- Gopalakrishnan, S., Sathya, A., Vijayabharathi, R., Varshney, R. K., Gowda, C. L., & Krishnamurthy, L. (2015). Plant growth promoting rhizobia: challenges and opportunities. *3 Biotech*, 5(4), 355-377.
- Graham, P. H. (2008). Ecology of the root-nodule bacteria of legumes. In *Nitrogen-fixing leguminous symbioses* (pp. 23-58). Dordrecht : Springer Netherlands..
- Grönemeyer, J. L., Kulkarni, A., Berkelmann, D., Hurek, T., & Reinhold-Hurek, B. (2014). Rhizobia indigenous to the Okavango region in Sub-Saharan Africa: diversity, adaptations, and host specificity. *Applied and environmental microbiology*, 80(23), 7244-7257.
- Guinet, M. (2019). *Quantification des flux d'azote induits par les cultures de légumineuses et étude de leurs déterminants : comparaison de 10 espèces de légumineuses à graines* (Doctoral dissertation, Université Bourgogne Franche-Comté).
- Hasan, M. (2018). Effect of rhizobium inoculation with phosphorus and nitrogen fertilizer on physico-chemical properties of the groundnut soil. *Environment and Ecosystem Science*, 2(1), 04-06.
- Jaiswal, S. K., Mohammed, M., Ibny, F. Y., & Dakora, F. D. (2021). Rhizobia as a source of plant growth-promoting molecules: potential applications and possible operational mechanisms. *Frontiers in Sustainable Food Systems*, 4, 619676.
- Jensen, E. S., Carlsson, G., & Hauggaard-Nielsen, H. (2020). Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. *Agronomy for sustainable development*, 40(1), 5.
- Kalra, Y. P., & Maynard, D. C. (1991). *Methods manual for forest soil and plant analysis* (No. NOR-X-319, pp. viii+-116).
- Kasongo, L. M. E., Mwamba, M. T., Tshipoya, M. P., Mukalay, M. J., Useni, S. Y., Mazinga, K. M., & Nyembo, K. L. (2013). Réponse de la culture de soja (*Glycine max* L.(Merril) à l'apport des biomasses vertes de *Tithonia diversifolia* (Hemsley) A. Gray comme fumure organique sur un Ferralsol à Lubumbashi, RD Congo. *Journal of Applied Biosciences*, 63, 4727-4735.
- Kasu-Bandi, B. T., Kitengie, F. K., Bagaluza, J. L., Nkolomini, A. B., Lenge, E. K., & Lubobo, A. K. (2021). Effects of Bradyrhizobium japonicum on nitrogen content in soybean leaves and seeds cultivated on acidic soils.
- Kebede, E. (2021). Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. *Frontiers in Sustainable Food Systems*, 5, 767998.
- Khojely, D. M., Ibrahim, S. E., Sapey, E., & Han, T. (2018). History, current status, and prospects of soybean production and research in sub-Saharan Africa. *The Crop Journal*, 6(3), 226-235.
- Książak, J., & Bojarszczuk, J. (2022). The effect of mineral N fertilization and Bradyrhizobium japonicum seed inoculation on productivity of soybean (*Glycine max* (L.) Merrill). *Agriculture*, 12(1), 110.
- Kyei-Boahen, S., Savala, C. E. N., Muananamuale, C. P., Malita, C., Wiredu, A. N., Chibeba, A. M., ... & Chikoye, D. (2023). Symbiotic effectiveness of Bradyrhizobium strains on soybean growth and productivity in Northern Mozambique. *Frontiers in Sustainable Food Systems*, 6, 1084745.
- Laurent, L. H., DUPONT, S., DUBUS, I., & BECQUER, T. (1998). Carence et fixation du phosphore dans les sols ferrallitiques ferritiques de Nouvelle-Calédonie Phosphorus deficiency and fixation in Geric Ferralsols of New Caledonia.
- LAZALI, M., BRAHIMI, S., BENADIS, C., & DREVON, J. J. (2020). Stratégies et mécanismes d'adaptation des légumineuses à la faible disponibilité des sols en phosphore. *Revue Marocaine des Sciences Agronomiques et Vétérinaires*, 8(3).

- Lesueur, D., Yacouba, T., Galiana, A., & Mallet, B. (1994). Croissance et nodulation d'Acacia mangium. Effet de l'inoculation avec Rhizobium dans trois types de sol désinfectés de basse Côte d'Ivoire.
- Louis, B. L., Laurent, K. K., Maurice, K. K., Michel, M. K., Dominique, T. T., & Luciens, N. K. (2015). Influence du semis tardif sur la croissance et le rendement du soja (Glycine max Merril) cultivé sous différents écartements à Lubumbashi, RD Congo [Influence of late sowing on growth and yield of Soybean (Glycine max Merril) grown under different spaces in Lubumbashi, DR Congo]. *International Journal of Innovation and Applied Studies*, 12(1), 104.
- Lupwayi, N. Z., Clayton, G. W., & Rice, W. A. (2006). Rhizobial inoculants for legume crops. *Journal of Crop Improvement*, 15(2), 289-321.
- Manyong, V. M., Smith, J., Weber, G. K., Jagtap, S. S., & Oyewole, B. (1996). Macro-characterization of agricultural systems in West Africa: An overview. *Resource and Crop Management Monograph*, 21, 33.
- Matías-Ramos, M., Hidalgo-Moreno, C. I., Fuentes-Ponce, M., Delgadillo-Martínez, J., & Etchevers, J. D. (2023). Potencial de especies de leguminosas mejoradoras de la fertilidad del suelo en regiones tropicales. *Revista mexicana de ciencias agrícolas*, 14(4), 531-541.
- McCully, M. E. (2001). Niches for bacterial endophytes in crop plants : a plant biologist's view. *Functional Plant Biology*, 28(9), 983-990.
- McKeague, J. A., & Stobbe, P. C. (1978). History of soil survey in Canada 1914-1975.
- Mendoza-Suárez, M., Andersen, S. U., Poole, P. S., & Sánchez-Cañizares, C. (2021). Competition, nodule occupancy, and persistence of inoculant strains: key factors in the rhizobium-legume symbioses. *Frontiers in Plant Science*, 12, 690567.
- Montgomery, D. C. (2017). *Design and analysis of experiments*. John wiley & sons.
- Moreira, F. M., Huisng, E. J., & Bignell, D. E. (2012). *A handbook of tropical soil biology: sampling and characterization of below-ground biodiversity*. Routledge.
- Motomizu, S., Wakimoto, T., & Tôei, K. (1983). Spectrophotometric determination of phosphate in river waters with molybdate and malachite green. *Analyst*, 108(1284), 361-367.
- Mukalay, M. H. J. (2016). Identification et classification des sols sous les nouvelles normes et étude de bio-identification et restauration des unités dégradées dans la zone agricole du Haut-Katanga/RD Congo. *Université de Lubumbashi, Lubumbashi*.
- Mullen, M. D., Israel, D. W., & Wollum, A. G. (1988). Effects of Bradyrhizobium japonicum and soybean (Glycine max (L.) Merr.) phosphorus nutrition on nodulation and dinitrogen fixation. *Applied and environmental microbiology*, 54(10), 2387-2392.
- N'gbesso, M. F., N'guetta, A. S., Kouamé, N., & Bi, K. F. (2010). Evaluation de l'efficience de l'inoculation des semences chez 11 génotypes de soja (Glycine max L. Merril) en zone de savane de Côte d'Ivoire. *Sciences & Nature*, 7(1).
- Nápoles, M. C., Cabrera, J. C., Varela, M., González-Anta, G., Nogueras, F., Cricco, J., ... & Meira, S. (2009). Influencia de inoculantes y factores edáficos en el rendimiento du soya. *Cultivos Tropicales*, 30(3), 18-22.
- Naudin, C. (2009). *Nutrition azotée des associations Pois-Blé d'hiver (Pisum sativum L.-Triticum aestivum L.): Analyse, modélisation et propositions de stratégies de gestion* (Doctoral dissertation, Université d'Angers).
- Nguyen, H. P., Miwa, H., Obirih-Opereh, J., Suzuki, T., Yasuda, M., & Okazaki, S. (2020). Novel rhizobia exhibit superior nodulation and biological nitrogen fixation even under high nitrate concentrations. *FEMS microbiology ecology*, 96(2), fiz184.
- Nyoki, D., & Ndakidemi, P. A. (2014). Effects of Bradyrhizobium japonicum inoculation and supplementation with phosphorus on macronutrients uptake in cowpea (Vigna unguiculata (L.) Walp). *American Journal of Plant Sciences*, 2014.
- Nyoki, D., & Ndakidemi, P. A. (2018). Selected chemical properties of soybean rhizosphere soil as influenced by cropping systems, rhizobium inoculation, and the supply of phosphorus and potassium after two consecutive cropping seasons. *International Journal of Agronomy*, 2018(1), 3426571.
- Okereke, G. U., Onochie, C., Onunkwo, A., & Onyeagba, E. (2001). Effectiveness of foreign bradyrhizobia strains in enhancing nodulation, dry matter and seed yield of soybean (Glycine max L.) cultivars in Nigeria. *Biology and Fertility of Soils*, 33(1), 3-9.
- Olivier N'goran, K. (2019). Effet de l'inoculum bactérien de la souche IRAT-FA 3 de Bradyrhizobium japonicum sur la production de trois variétés de soja en Côte d'Ivoire. *International Journal of Biological and Chemical Sciences*.
- Raimi, A., Adeleke, R., & Roopnarain, A. (2017). Soil fertility challenges and Biofertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, 3(1), 1400933.
- Razafintsalama, H., Trap, J., Rabary, B., Razakatiana, A. T. E., Ramanankierana, H., Rabeharisoa, L., & Becquer, T. (2022). Effect of Rhizobium inoculation on growth of common bean in low-fertility tropical soil amended with phosphorus and lime. *Sustainability*, 14(9), 4907.
- Reid, D. E., Ferguson, B. J., Hayashi, S., Lin, Y. H., & Gresshoff, P. M. (2011). Molecular mechanisms controlling legume autoregulation of nodulation. *Annals of botany*, 108(5), 789-795.
- Revellin, C., Pinochet, X., Beauclair, P., & Catroux, G. (1996). Influence of soil properties and soya bean cropping history on the Bradyrhizobium japonicum population in some French soils. *European journal of soil science*, 47(4), 505-510.
- Richards, L. A. (Ed.). (1954). *Diagnosis and improvement of saline and alkali soils* (No. 60). US Government Printing Office.
- Richardson, A. E., Lynch, J. P., Ryan, P. R., Delhaize, E., Smith, F. A., Smith, S. E., ... & Simpson, R. J.

(2011). Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant and soil*, 349(1), 121-156.

- Rodríguez-Navarro, D. N., Margaret Oliver, I., Albareda Contreras, M., & Ruiz-Sainz, J. E. (2011). Soybean interactions with soil microbes, agronomical and molecular aspects. *Agronomy for Sustainable Development*, 31(1), 173-190.
- Roose, E. (2007). Restauration de la productivité des sols tropicaux. *Gestion intégrée des eaux et des sols: Ressources, aménagements et risques en milieux ruraux et urbains, Hanoi (Vietnam)*.
- Saint Macary, H. (1990). Fixation symbiotique de l'azote en milieu tropical. Quelles applications ? Quelles limitations ? CIRAD-IRAT.
- Smith, D. L., & Hume, D. J. (1987). Comparison of assay methods for N2 fixation utilizing white bean and soybean. *Canadian Journal of Plant Science*, 67(1), 11-19.
- Solomon, T., Pant, L. M., & Angaw, T. (2012). Effects of inoculation by *Bradyrhizobium japonicum* strains on nodulation, nitrogen fixation, and yield of soybean (*Glycine max* L. Merill) varieties on nitisols of Bako, Western Ethiopia. *International Scholarly Research Notices*, 2012(1), 261475.
- Temegne, N. C., Ajebesone, F. N., & Kuate, A. F. (2015). Influence de la composition chimique du sol sur la teneur en éléments nutritifs et le rendement du manioc (*Manihot esculenta* Crantz, Euphorbiaceae) dans deux zones agro-écologiques du Cameroun. *International journal of biological and Chemical Sciences*, 9(6), 2776-2788.
- Tetteh, F. M., Quansah, G. W., Frempong, S. O., Nurudeen, A. R., Atakora, W. K., & Opoku, G. (2017). Optimizing fertilizer use within the context of integrated soil fertility management in Ghana. In *Fertilizer use optimization in sub-Saharan Africa* (pp. 67-81). GB: CABI.
- Thies, J. E., Singleton, P. W., & Bohlool, B. B. (1991). Influence of the size of indigenous rhizobial populations on establishment and symbiotic performance of introduced rhizobia on field-grown legumes. *Applied and environmental microbiology*, 57(1), 19-28.
- Tshibuyi Kasu-Bandi, B., Kidinda Kidinda, L., Banza Mukalay, J., Assani Bin Lukangila, M., Baboy Longanza, L., Kasongo Lenge, E., & Kanyenga Lubobo, A. (2019). Effects of *Bradyrhizobium japonicum* on Some Chemical Properties of Ferralsols under Soybean (*Glycine max* (L.) Merr.) Cultivation. *American Journal of Agricultural and Biological Sciences*, 14.
- Van Zwieten, L., Rose, T., Herridge, D., Kimber, S., Rust, J., Cowie, A., & Morris, S. (2015). Enhanced biological N2 fixation and yield of faba bean (*Vicia faba* L.) in an acid soil following biochar addition : dissection of causal mechanisms. *Plant and Soil*, 395(1), 7-20.
- VéRICEL, G., & Minette, S. (2010). Mieux gérer l'interculture pour un bénéfice agronomique et environnemental. Légumineuses, comment les utiliser comme cultures intermédiaires. *Brochure de la Chambre Régionale d'Agriculture, Poitou Charentes*.
- Wobeng, N. B. M., Banfield, C. C., Megueni, C., Mapongmetsem, P. M., & Dippold, M. A. (2020). Impact of legumes on soil microbial activity and C cycle functions in two contrasting Cameroonian agro-ecological zones. *Pedobiologia*, 81, 150662.
- Woomer, P. L., Baijukya, F., & Turner, A. (2012). Progress towards achieving the vision of success of N2Africa. *Success of N*, 2.
- Zoundji, M. C. C., Tossou, H., Balogoun, I., Akplo, T. M., Gangnon, S. O., Tossou, O., ... & Houngnandan, P. (2024). Effet résiduel de l'inoculation rhizobienne du soja [*Glycine max* (L.) Merrill] sur la fertilité du sol et la productivité du maïs semé en rotation au Bénin. *International Journal of Biological and Chemical Sciences*, 18(2), 375-388.